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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) ILC, INC. 164 Commercial Street Sunnyvale, California 94086	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

HIGH POWER ALKALI VAPOR LAMPS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Semi-Annual Technical Report 1 December 1970 to 30 October 1971

5. AUTHOR(S) (First name, middle initial, last name)

Lowell Noble

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1971	52	14

8a. CONTRACT OR GRANT NO. N00014-71-C-0183	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) R-ILC-71-29
d.	

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Advanced Research Projects Agency Office of Naval Research Dept. of the Navy Arlington, Virginia 22217

13. ABSTRACT

The objective of this contract is to develop and deliver prototype 8kW (input) alkali vapor lamps that emit 2 kW of output radiation in the major pumping bands of Nd:YAG laser material. The lamps are to be 10 inches long and 18mm or less in diameter; be readily recycled, and provide operational lifetimes of 100 hours or more. Lamps with transparent sapphire envelopes, 14.5mm in bore diameter, were built and operated successfully at input powers per unit length of 0.5kW/inch, more than one-half the design goal. These lamps were more efficient in pumping Nd:YAG than krypton arc lamps of the same length and input power, in spite of the fact that the alkali vapor pressure has not yet been adjusted to provide optimal spectral matching to the laser pumping bands. Also, tests on smaller bore lamps indicate that adding excesses of argon or mercury to the standard K-Rb fill does not produce significant improvements in spectral matching. Spectrophotometric and calorimetric equipment developed for the program is described.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical Pumps						
CW Lamps						
Alkali Metal Lamps						
Krypton Arc Lamps						
Lasers						
Lasers Pumping						

HIGH POWER ALKALI VAPOR LAMPS

SEMIANNUAL TECHNICAL REPORT

DDC
RECEIVED
JAN 26 1972
B

OFFICE OF NAVAL RESEARCH
CONTRACT NO. N00014-71-C-0183
CONTRACT AMOUNT: $75,000

EFFECTIVE DATE:	1 December 1970
EXPIRATION DATE:	31 December 1971

Principal Investigator: Mr. Lowell Noble
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Arlington, Virginia 22217

Sponsored by:

ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 306
Program Code No. S0507A

Prepared by:

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ABSTRACT

The objective of this contract is to develop and deliver prototype 8kW (input) alkali vapor lamps that emit 2kW of output radiation in the major pumping bands of Nd:YAG laser material. The lamps are to be 10 inches long and 18mm or less in diameter; be readily recycled, and provide operational lifetimes of 100 hours or more. Lamps with transparent sapphire envelopes, 14.5mm in bore diameter, were built and operated successfully at input powers per unit length of 0.5kW/inch, more than one-half the design goal. These lamps were more efficient in pumping Nd:YAG than krypton arc lamps of the same length and input power, in spite of the fact that the alkali vapor pressure has not yet been adjusted to provide optimal spectral matching to the laser pumping bands. Also, tests on smaller bore lamps indicate that adding excesses of argon or mercury to the standard K-Rb fill does not produce significant improvements in spectral matching. Spectrophotometric and calorimetric equipment developed for the program is described.

FOREWARD

This work is being carried out by the Engineering Division of ILC, which is under the direction of Dr. L. Reed. The Technical Monitor of the program is Dr. Fred Quell, Office of Naval Research.

Mr. L. Noble is the principal investigator. He is assisted by Dr. C.B. Kretschmer. Mr. B. Maynard performs the experimental measurements and data reduction. Mr. J. Gaspar is responsible for alkali vapor lamp fabrication.

Work under this contract began on 5 March 1971. This report covers the work accomplished through 31 October 1971. On 29 November 1971, ILC requested a three month extension of the contract, to 31 March 1972.

SUMMARY

Alkali metal vapor lamps are being developed that are 10 inches long and 18mm in diameter, that handle 8 kW of input power, and that should deliver 2 kW of output radiation in the major pumping bands of Nd:YAG laser material. These lamps are intended to replace krypton arc lamps in a 10 inch long segmented-disc laser being developed elsewhere for ONR.

Alkali metal lamps that pump Nd:YAG with high efficiencies have been made previously in the 1 kW input power range. The lamp is limited by laser cavity considerations to 10 inch length and 18mm O.D.; construction considerations limit the bore diameter to a maximum of 14.5mm. At 8 kW input, the lamp's physically limiting parameter is thermal wall loading. A K-Rb mixture has been found to be the optimal alkali metal plasma material. Efficiency for pumping Nd:YAG is optimized by adjusting the operating vapor pressure of the alkali metal vapor to obtain the correct amount of self-absorption of the alkali metal resonance lines.

Experimental lamps were constructed with 14.5mm bore diameter, but only 3 inch arc length; since input power in these lamps is known to scale linearly with length, these shorter lamps provide all the needed data at considerable savings over 10 inch long lamps. Lamps with smaller bores were constructed for determining the effects of additions to the standard K-Rb filling, and for determining the effect of bore diameter on arc diameter and efficiency. Krypton arc lamps were also constructed for comparison with the alkali vapor lamps, and to test the measuring equipment being used in the program.

The effective irradiance of the lamps was measured spectrophotometrically, using a time-shared computer system to calculate, in absolute units, the amount of light emitted by the lamp that is absorbed in the pumping bands of the laser material.

In addition, the fluorescence excited by the lamp was measured in a sample of the laser material under controlled conditions. A flow calorimeter was constructed for measuring the total radiative efficiency of the lamps.

14.5mm bore K-Rb lamps were successfully operated at input levels of more than one half the design goal (800W/inch). The spectra indicated that these lamps were being operated at too high a vapor pressure to give an optimal spectral match to the laser material. In spite of this, these lamps gave significantly greater output in the Nd:YAG pumping bands, at the same input power, than a 10mm bore krypton arc lamp equivalent to the krypton arc lamp that these K-Rb lamps are intended to replace.

The difficulty in obtaining the desired vapor pressure is believed to be caused by the fact that liquid alkali metal creeps along the inside surface of the tubulation to regions of higher temperature than that of the cold spot, which is intended to control the vapor pressure. Future lamps will incorporate design modifications intended to circumvent this difficulty.

The diameter of the arc, which nearly filled the bore in a 3mm envelope, was found to increase only very slowly as the envelope diameter was increased, and was only slightly greater than 4mm in the 14.5mm envelope, even though the input power was much greater in the larger bore lamp. This means that the ability of the lamp to absorb an increased input power is obtained mainly by increasing the temperature (and therefore the conductivity) of the arc rather than by increasing its diameter.

Measurements on smaller bore lamps indicated that the addition of excesses of argon or mercury to the standard K-Rb filling did not increase the effective

irradiance, although the spectrum of the lamp with excess mercury gave some evidence of molecular band emission on the long wavelength side of the alkali resonance lines.

A lamp constructed with a BeO envelope was operated successfully. It eventually failed by leakage through many pinholes in the ceramic after operating for 16 hours. It is expected that this source of failure can be eliminated by improved manufacturing methods for the BeO envelope material.

Calorimetric measurements on krypton arc lamps indicated that the radiative efficiency increases with both bore diameter and input power, and approaches 50% at full rated power.

It is anticipated that satisfactory control over the vapor pressure will be obtained during the next reporting period, and that it will be possible to operate large bore alkali lamps at the design goal input power of 800 W/inch. When this has been accomplished, construction of the full-length 8 kW lamps will be started. Extrapolation of the results obtained so far indicates that, at the full rated input power, the effective irradiance of the alkali lamps will be significantly greater than that of a 10mm bore krypton arc at the same input power.

LIST OF ILLUSTRATIONS

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1.0 INTRODUCTION AND OBJECTIVES

This high power alkali metal vapor lamp program is a consequence of the recent development of lower power sapphire envelope alkali metal lamps that efficiently pump Nd:YAG lasers,[1] and of a need for reducing thermal dissipation in a high power, segmented disc, axial gradient, Nd:YAG laser now under development. The laser work is being carried out elsewhere under ONR sponsorship.[2] The specific lamp being developed on this program for that laser has the following design goals:

Input power to lamp	8 kW
Lamp output in the main Nd:YAG pump bands (0.7-0.95μ)	2 kW
Source geometry (arc radiance)	Optimized to maximize useful pump lamp output
Lamp geometry	8-10 inch length, 18mm maximum outside diameter
Life	100 hours

Krypton arc lamps are also involved in this program: they are used to aid in the development of measurement equipment, and for efficiency comparisons with the alkali metal lamps being developed.

2.0 BACKGROUND

The excitation spectrum for Nd:YAG is shown in Figure 1. For the past five years sapphire envelope alkali metal vapor arc lamps have been investigated as potentially more efficient than noble gas arc lamps for pumping Nd:YAG lasers.[3,4,5]

Both quartz jacketed and "nude" sapphire envelope lamps have been developed[1] and are illustrated in Figure 2. Laser output data indicates that K-Rb vapor lamps are more efficient than krypton lamps for pumping Nd:YAG, at least up to input powers of 1kW. Three inch length, 5mm and 6.2mm bore, lamps were used to provide the data shown in Figure 3.

The limitation of 18mm O.D. on the lamp being developed on this contract imposes a 14.5mm maximum inside diameter on a sapphire envelope because the minimum wall thickness available in this diameter of sapphire is 0.75mm, and a 0.5mm vacuum gap is required between the sapphire (inner) envelope and the 0.5 mm thick quartz outer envelope. Since this lamp handles 8kW input and is 10 inches long, the 14.5mm bore diameter gives rise to an inner wall loading of 70 W/cm^2. It has been found previously that 100 hour lamp life can be obtained when a lamp is operated at this power level in a free radiating environment.

In order to achieve the desired pumping efficiency, the lamp radiation must be optimally matched to the laser excitation pump bands. An optimally matched K-Rb vapor lamp spectrum obtained on a prior program[1] is shown in the lower part of Figure 4.

The radiation emitted from alkali metal vapor that is useful for pumping lasers is the reversed resonance radiation. Resonance radiation results from a change in the energy level of an excited atom between the lowest excited state above the ground state to the ground state. Because the ground state is well populated, the resonance radiation emitted can easily excite another ground state atom to the first excited state. Thus the radiation and energy levels can "resonate" many times before the radiation is finally emitted from the plasma. This radiation will be increasingly trapped at higher and higher (pressure x thickness) products as is sequentially shown in the potassium spectrum progression, Figure 5 (due to Schmidt in the pioneer study in this field[7]), resulting in a reversal of the center line of the resonance radiation. The phenomenon of resonance radiation reversal is used to obtain an optimum match to the Nd:YAG pump bands by adjusting the pressure in a lamp as a function of its bore diameter.

In arcs more than 1 inch long the emitted radiation scales linearly with power input to the arc. Thus, a 3 inch, 3 kW arc emits as efficiently as an 8 inch, 8 kW arc.

It has been found that an alkali vapor arc lamps' efficiency for laser pumping depends upon:

1. The plasma material(s); K, Rb, Na, (Hg)
2. The vapor pressure of the alkali metal vapor, which is controlled by the cold spot temperature of the lamp.
3. The thickness of alkali metal vapor through which the radiation must travel, which is a function of the bore diameter of the lamp.
4. The power density in the lamp.

The success with which reversed radiation can be matched to the Nd:YAG bands can be demonstrated by interposing a slab of Nd:YAG material between the lamp and an emission sensor. A typical subtractive spectrum obtained by this technique, using an 0.25 inch thick Nd:YAG slab, is shown in the upper spectrum in Figure 4.

The wavelengths of the resonance radiation emitted by the alkali metal vapors are as follows:

Lithium	6103Å	6707Å
Sodium	5890Å	5896Å
Potassium	7665Å	7699Å
Rubidium	7800Å	7948Å
Cesium	8521Å	8943Å

Mixtures of vapors, such as a mixture of K-Rb, will display an overlap of the resonance radiation lines, and the selection of the correct alkali metal or mixture of metals will basically determine the coupling efficiency of the radiation from the arc to the Nd:YAG rod. At low vapor pressures and/or vapor thicknesses the radiation will be emitted at the resonance wavelengths, but, as discussed above, at higher pressures and/or increased vapor thicknesses it will reverse and at some point pass through the stage at which the wings of the reversed resonance radiation will match the excitation spectra of Nd:YAG. Obviously, the larger the lamp diameter the lower the pressure at which this will occur. Thus the large bore lamps used on this program should display an optimum match at a lower pressure than the 5mm bore lamps previously investigated.(1)

As the power density of a plasma increases, the energy available for exciting the alkali metal atoms to higher energy levels increases. This

occurs at the expense of the lower level transitions giving rise to resonance radiation; thus it is desirable to operate at as low a power density as possible. If the plasma is wall confined, then obviously the bore diameter of the lamp controls the power density. However, it has been found[1] in both alkali metal vapor and krypton CW arc lamps that, although the arc is wall-stabilized, it is not wall confined as it is in high power density pulsed lamps. Consequently some control over power density other than controlling the power into the lamp must be achieved by using indirect techniques such as pressure control and secondary arc dopants.

The measurement of arc diameter is an important diagnostic tool that is used to determine the effect of varying parameters or arc expansion and hence on power density in the arc.

From this brief review we can see that the lamp parameters pertinent to this program are:

1. the plasma material.
2. the alkali metal vapor pressure
3. within certain limits, the bore diameter
4. active or inactive additions to the alkali metal vapor, such as mercury and argon
5. within certain limits, the length of the lamp.

3.0 EXPERIMENTAL APPROACH

The successful development of an efficient 5 kW lamp will represent a significant advance in alkali metal laser pump technology, as the maximum diameter lamp previously developed has an 8mm outside diameter

and a 1 kW power limitation .

At the start of this program it was unknown whether the effects of increased bore diameter of the 8 kW lamp could be compensated for by adjusting the other allowable lamp parameters to maintain the necessary line reversal.

Two early possibilities were considered for increasing the wall loading capability of the lamp and hence reducing its bore diameter. These involved the use of thinner wall sapphire lamps and the use of beryllium oxide envelopes. In both cases the thermal stress resistance of the lamps could be increased.

Thin wall sapphire tubing in the required bore diameter was not available at the start of this work, but beryllium oxide in translucent polycrystaline form could be obtained and one small bore lamp was constructed of this material.

The efficiency of lamps is generally independent of arc length for arcs longer than 1 inch, as long as the input power per unit length of the lamp is constant. Lamps with 14.5mm bore and 3 inch arc length were used on this program in order to lower lamp fabrication costs and to allow the use of lower-power test equipment.

In addition to the 14.5mm bore lamps, 5mm and 6.3mm bore, three inch arc lamps (identical with those used on a prior alkali metal program[1]) were used to (a) determine whether the addition of mercury or
argon would increase the laser pumping efficiency of K-Rb lamps; and (b) to compare their arc sizes with those of larger lamps as part of the power

density and radiance studies. Krypton arc lamps were also constructed.

4.0 EXPERIMENTAL PROCEDURE

4.1 Lamp Construction

4.1.1 Alkali Metal Vapor Lamps

All but one* of the alkali vapor lamps had sapphire envelopes (from Tyco) and Niobium + 1% Zr end caps, a tantalum tubulation, and tungsten electrodes. The construction followed the fabrication processes previously developed.[1] The 5 and 6.3mm bore by 3 inch arc length lamp structures are shown in Figure 2. The cross-section diagram of the 14.5mm bore, 3 inch arc length lamp is shown in Figure 6, and a lamp enclosed in a quartz envelope is shown in Figure 7. The end caps are sealed to the sapphire using an active alloy at 1350°C. The alkali metal is introduced into the lamp via the tantalum tubulation, which is then pinched off and electron-beam welded. During operation, the end of the tubulation becomes the cold spot of the lamp and the reservoir for the unvaporized alkali metal. The cold spot normally controls the vapor pressure of the alkali metal within the lamp. The cold spot can be either heated or cooled in order to achieve the correct pressure in the lamp.

For bare lamps operated in a vacuum bell jar, heating is accomplished by a nichrome heater in contact with the cold spot.

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*One BeO lamp was [illegible].

Cooling in the 5 and 6.3mm bore lamps is accomplished by attaching radiation fins to the cold spot tubulation and, for the large lamps, by a forced-convection water-cooled arrangement that cools a copper block that, in turn, is in intimate contact with the cold spot of the lamp. For quartz envelope lamps, split carbon blocks provide the thermal path from the lamp cold spot to the outside world. The quartz outer envelope is shrunk down over the carbon to provide a continuous conduction path. The shrunk-down quartz region can be heated with a spiral nichrome heater or cooled by a forced air convection flow.

The lamps are started with a high voltage low current pulse of several thousand volts. A low pressure argon (50 Torr) fill assists in arc initiation. The lamps are then gradually brought up to power over a several-minute period in order to allow the alkali metal to vaporize and to form a stable arc, and to minimize transient thermal stresses on the sapphire envelope.

A dc power supply is normally used for this operation. The alkali metal lamp requires "seasoning" for the first hour of its operation, after which the measurements described in the next section may be performed.

Small bore alkali metal lamps were constructed with the standard fill found to be optimum on a prior program[1], i.e., a 50:50 mix of K-Rb with a 50 Torr addition of argon starter

gas. Two lamps were also constructed with a variation of this fill. 3000 Torr of argon was added to the K-Rb fill in one lamp, and mercury was added to the K-Rb fill in another lamp.

A BeO envelope, 5mm bore x 3 inch arc length, was also constructed with a new metalizing procedure. The lamp was filled with K-Rb as the active alkali vapor material and 50 Torr of argon for the starting gas.

An 8 kW alkali metal lamp of 14.5mm bore diameter has a wall loading, for an 8 inch length, of 90 W/cm^2, and for a 10 inch length, of 70 W/cm^2. A lamp life of 100 hours can be routinely expected at the 70 W/cm^2 figure[(1)] if in a free radiation condition.

In order to conserve on material expenditures and test facilities, the development lamps are being constructed with the 14.5mm bore diameter but with a reduced arc length of 3 inches; power is known to scale linearly with length, while the scaling parameters are not known for the radial direction. The 8-10 inch length lamps will be constructed when the efficiency goals have been reached on the shorter test lamps.

4.1.2 Krypton Lamp Construction

Standard ILC externally water cooled lamps of 4, 6 and 10mm bore diameter and 3 inch arc length were constructed

and filled to 3 atmospheres. A krypton lamp with electrodes internally cooled by water was constructed with 10 mm bore diameter, and filled with 3 atmospheres of krypton. The lamp was designed to be superior to the presently used (externally water cooled) lamp. It was tested and later filled to 7 atmospheres of krypton. The krypton lamps are illustrated in Figures 8 and 9.

4.2 Spectral Measurements

4.2.1 Absolute Spectral Irradiance and Radiance Measurements

The measurements taken on this program utilize the procedures recommended by the N.B.S.

Spectral irradiance measurements were made which, together with calorimetric measurements, describe the lamps' electro-optical conversion efficiency in the 0.7-0.95μ band. Below 0.5μ the calibration of the standard lamp is by extrapolation, so that data in this region must be treated with reserve.

Radiance measurements were made to provide a measure of the ability to focus the radiation from the lamp onto the laser rod within a focusing cavity.

The lamp is mounted in a Pyrex vacuum bell jar for making spectral irradiance measurements. The mounting is keyed to an optical bench so that the lamp is precisely and reproducibly aligned to the detector system, which is mounted at 50 cm distance from the lamp.

The lamp emission spectra were taken with a Jarrell Ash 1/4 meter monochromator, using a photomultiplier detector with an extended-range S-1 phosphor. The system response was initially determined using an Eppley standard irradiance lamp (traceable to NBS) as a reference.

All output data were digitized onto punched paper tape for input to a computer memory. The system response curve is also stored in the computer memory. The spectral curves are corrected for the system response and plotted on an XY recorder over the range of 0.4μ to 1.6μ. Time-shared computer processing allows a rapid (approximately 2 minute time lag) determination of the spectral irradiance in the 0.4 to 1.6μ band.

Spectral radiance measurements are made by comparison with an Eppley standard radiance lamp.

4.2.2 Relative "Effective" Irradiance Measurements

In addition to these two standard measurements, several relative measurement techniques have been developed for use with lamps for pumping lasers.

The first technique involves a computerized integration of the spectral irradiance curve multiplied by the absorption

coefficient of Nd:YAG, which has been previously digitized and entered into the computer. The quantity that is obtained is the _effective_ spectral irradiance of the lamp and is measured in terms of watts per cm^2 per nanometer per unit thickness of laser material for a single pass of lamp radiation. A block diagram of the equipment used in this operation is shown in Figure 10. Figure 4 gives a subtractive spectrum of the alkali metal radiation absorbed in the Nd:YAG in a single pass by using an actual 0.25 thick slab of Nd:YAG rather than by using the Nd:YAG curve entered into the computer.

A second special technique involves measurement of the effective irradiance emitted from a lamp by using a differential Nd:YAG fluorescence analysis method. This method was first devised for use in a cylindrical integrating cavity arrangement for low power lamp measurements, and has previously been described in detail.[1] A schematic diagram of this arrangement is in Figure 11. The integrating cavity technique was used to take measurements on the small bore lamps evaluated on this program.

This fluorescence analysis technique has now been adapted to enable measurements to be carried out to the 8 kW level. This modified arrangement is shown in Figure 12. The integrating cavity arrangement is replaced with a direct irradiance measurement of the lamp as it is operated in the

vacuum bell jar. A precision holder was fabricated so that the two radiation sensing units could be positioned at a precise distance from the lamp. The sensors are mounted external to the bell jar. They consist of 0.25 inch thick undoped YAG and doped Nd:YAG rectangular slabs of material, behind each of which is placed a 1.06μ transmission filter and a PIN diode. The PIN diodes convert any radiation impinging on them to a millivoltage. The scattered light signal from the diode behind the undoped YAG is electrically subtracted from the fluorescence plus scattered light signal produced by the other diode. A relative measure of the amount of lamp radiation that is converted to 1.06μ fluorescence radiation is thus obtained in terms of a fluorescent output voltage (FOV).

The use of this FOV technique provides a rapid iterative technique for optimizing a lamp at a given power level by progressively adjusting the cold spot temperature, and thus the pressure in the lamp, and plotting this quantity against the FOV reading. The FOV maximum on this curve corresponds to an optimum match of the alkali metal lamp to the Nd:YAG material. This procedure can be carried out from the ignition point of the lamp up to the highest operating point at which the lamp can be safely operated. A curve is obtained somewhat similar to a laser power slope efficiency curve. Plots of FOV versus lamp input power can be compared for different lamps, and their relative effective irradiances can be determined.

This device has previously proven itself as a means of providing a rapid lamp selection technique to the point where now, at ILC, it is carried out before other photometric tests are performed. Spectra are then taken at the lamp operating conditions corresponding to the maximum FOV reading, and occasionally also at operating points on each side of this condition in order to confirm the FOV data by examining the under-reversed and over-reversed operating condition.

4.3 Calorimetric Measurements

The calorimetric measurements are used to determine the total, and the 0.3 to 1.3μ, radiation efficiency of the krypton and the alkali vapor arc lamps. In conjunction with either a relative or an absolute lamp irradiance measurement over the 0.3 to 1.3μ region, these measurements can then be used to obtain the lamp radiation efficiency in any band within this range, such as the 0.7 to 0.95μ band.

A diagram of the experimental arrangement for making calorimetric measurements on a water cooled krypton lamp is shown in Figure 13. The lamp is centered in a quartz water jacket 1mm wall thickness, with a gap of about 1mm between the outside of the lamp and the inside of the water jacket. Cooling water flows through the gap at a rate of 1.0 gal/min. The cooling water temperature is 15° to 20°C. The flow rate is monitored by flowmeter 1 and the increase in temperature of the cooling water is

given by the difference in the readings of thermometers 1 and 2. This allows calculation of the envelope and electrode heat dissipation, P_h. The radiative output is measured by absorption in a calorimeter constructed from two concentric lengths of quartz tubing with a 6mm annular spacing. Water, either clear or made opaque by the addition of India ink, is circulated through the calorimeter, flowmeter 2, and a heat exchanger. The rise in temperature due to absorption of radiation by the 6mm layer of water is given by the difference in the readings of thermometers 3 and 4. The flow rate, which is maintained at about 0.6 gallons per minute, is monitored by flowmeter 2. This allows calculation, with the use of opaque water, of the total radiated power, P_r, and with clear water the amount of power outside the 0.3-1.3μ region. According to the curve of water absorption plotted against wavelength, which is shown in Figure 14, the radiation outside of the 0.3-1.3μ region will essentially all be absorbed by a 6mm thick water layer. The input power to the lamp is calculated from lamp voltage and current measurements (VxI). The efficiency is given by $P_r/(P_r+P_h)$, and a check on the accuracy of the measurements is possible through the fact that the VxI product should be equal to $P_r + P_h$. For each lamp, a series of readings is taken at different input power levels.

4.4 Arc Diameter Measurements

The arc image was projected directly onto a screen and the

diameter of the plasma was measured as a fraction of the cross-section of the sapphire envelope. Then, knowing the diameter of the envelope, the arc diameter is determined. The alkali metal lamps used for this test, as for the calorimetric test, were enclosed in quartz jackets as shown in Figure 2 and Figure 7.

5.0 EXPERIMENTAL RESULTS*

5.1 Results for 5mm and 6.3mm Bore, 3 Inch Arc Length Alkali Metal Vapor Lamps

The small bore alkali metal lamps were operated in evacuated quartz envelopes. Cooling of the inner sapphire envelope was by radiation; cooling of the outer quartz envelope was by free air convection. The cold spot temperature was regulated as discussed in the previous section. Details of the operation of lamps of these sizes have been discussed previously.(1) Their construction details are shown in Figure 2.

The beryllium oxide envelope lamp was operated successfully for sixteen hours at 500 watts. Failure was by multiple pin-hole leaks appearing in the center (highest temperature) portion of the ceramic. This mode of failure has often been noted in polycrystaline alumina envelope alkali metal lamps,(1) and apparently can be overcome by improving ceramic tube manufacturing techniques. About this time work under another contract was started to evaluate large diameter BeO envelope cesium lamps for pulsed applications(10) so further work on BeO lamps was

*The lamp numbers cited in this section refer to a recorded, chronological, sequential numbering of all developmental alkali metal lamps constructed at ILC.

deferred until results are generated on this other program.[10] It should be noted that, since the BeO envelopes are translucent, the effective radiating surface is the exterior of the envelope. Thus the radiance (brightness) of the lamp for laser pumping will be lower than when transparent sapphire envelopes of the same O.D. are used.

Lamps were constructed with 5mm bore and 3 inch arc lengths. These lamps were filled with K-Rb + 50 Torr of argon (No. 138), K-Rb + 3000 Torr of argon (No. 78), and K-Rb + 50 Torr argon + Hg, (No. 131). Spectra were taken on these lamps. The spectral data on the lamps with the fill variations is presented in Figures 15, 16, and 17. The integrated area of the spectrum that matches the pump bands of Nd:YAG was measured, and the areas were found to be equivalent.

FOV data were taken on the K-Rb and the K-Rb + Hg lamps. These comparative data are shown in Figure 18 and the FOV results are shown to be similar. FOV data was not taken on the 3000 Torr argon lamp, No. 138 as the primary point being explored with this lamp was the shift of the reversed resonance lines of the alkali metal species. No shift was noted.

The lamp, No. 131, with Hg in addition to the K-Rb fill material was operated ac at 0.5 to 20 kHz. Since the K-Rb lamps can be operated from standard krypton arc lamp dc power supplies, the development of the mercury additive lamps was not pursued further.

The results of the measurements of the arc diameters of the alkali metal plasmas, plotted against input power to the lamp, are presented in Figure 19.

5.2 Results for 14.5mm Bore, 3 Inch Arc Length K-Rb, 50 Torr Argon Fill Alkali Metal Vapor Lamps

Four K-Rb lamps were made according to the general design shown in Figure 6. The first lamp, No. 126, had a hole drilled into the side of the tantalum tubing that was positioned to be on the inside of the lamp. The hole allowed the lamp to be evacuated and then filled with the K-Rb/argon mixture. The lamp was operated with the cathode and cold spot "up" in the bell jar. During initial start up a locally high concentration of alkali metal liquid and vapor was present near the wall and caused an arc to form near the rear of the cathode. This created a hot spot on the sapphire wall near the seal area. The excessive thermal stress caused a crack to initiate at the hot spot, which catastrophically propagated the entire length of the lamp.

The second lamp, No. 157, was designed with the pump and fill exit hole drilled through the center of the anode in order to rectify the problem experienced with the first lamp. The lamp was first operated in the bell jar over the range of 400 W to 1000 W input with radiation cooling of the cold spot, as this technique had previously proved successful for smaller lamps.[1] Preliminary relative irradiance measurements employing both the differential fluorescence (FOV) analysis technique and spectral irradiance

determinations indicated that the lamp was being operated at too high a pressure, i.e., the spectrum was over-reversed. The cold spot temperature was reduced by increasing the area of the multiple-finned radiator surface to the greatest possible extent, but still the over-reversed condition persisted. At this point, it was decided to increase the heat removal from the cold spot via a water cooled copper block,* which was arranged to be in intimate contact with the tantalum tubing. Even with the cold spot near room temperature, the spectrum was still too widely reversed. This cooling technique eventually resulted in the lamp cracking in the sapphire-metal seal area due to too steep a temperature gradient between the seal area and the cold spot.

A third lamp, No. 130, was fabricated with a longer tantalum tubulation in order to prevent a recurrence of the envelope cracking. This lamp was successfully operated to 1400W of input power, and relative spectral irradiance and fluorescence power measurements (FOV) were taken. The FOV versus power input for this lamp, No. 130, is shown in Figure 20. The spectrum was still over-reversed despite a 40°C cold spot temperature being maintained. The spectrum is shown in Figure 21. This lamp subsequently failed by an arc-over to the ceramic-to-metal seal area when it was restarted with a supply that delivered a minimum of 6 amps rather than the 3 amp (minimum) supply customarily used. (The three amp supply was being used on a concurrent lamp experiment being carried out on this program.)

*At first an indium melt bath was used to control the cold spot temperature, following the procedure of Schmidt.[7] The indium bath technique was abandoned in favor of the direct conduction cooling path to the copper block, as it appeared that the lamp resonance line radiation was still over-reversed with the indium bath technique.

A fourth lamp, No. 137, was constructed and operated with an outer quartz envelope, Figure 7, in order to be able to carry out arc diameter measurements. The arc diameter measurements are shown in Figure 19. This lamp was operated up to 1300W using forced convection cooling. The lamp was operated cathode and cold spot "down". The lamp was still in operation at the end of this reporting period.

A maximum of five more 3 inch lamp starts are planned for the second semi-annual work period. Eight 10 inch lamp starts are also planned. Full power operation of the 3 inch lamp, i.e., approximately 2.4 kW, will require a redesign of the existing vacuum bell jar system; at the 1400 W level the bell jar is approaching the allowable thermal loading limit for Pyrex glass jar operation. (A metal bell jar system with a sapphire window is being fabricated.)

5.3 Results for 4, 6 and 10mm Bore, 3 Inch Arc Length, 3 Atmosphere Fill Krypton Arc Lamps

The krypton arc lamps with electrodes externally cooled by water were used to test the water calorimeter equipment constructed during this program. Krypton arc lamps were used because another efficiency measuring system, not compatible with alkali metal lamp operation, was available for checking the results. The cross check of the results gave an agreement of the total radiative efficiency to within 1%.

The total radiative efficiency results for the krypton lamps as a function of input power to the lamp, up to a maximum of 4 kW, is given in Figure 22.

The results of the calorimetric tests confirm the data reported in the literature,[12] i.e., the radiative efficiency increases with both lamp bore diameter and lamp input power.

The percentage of radiation from the 4mm bore lamp that is absorbed in the 6mm water thickness of the calorimeter is plotted against lamp output power in Figure 23. At the 4 kW lamp input power level, 46% of the input power is radiated and 15% of the radiated power or 7% of the input power is absorbed in the 6mm water layer of the calorimeter. This leaves 39% of the total input power to be radiated between 0.3 and 1.3μ.

Krypton lamp irradiance measurements were not made during this period. However, FOV measurements were made, using the bell jar arrangement shown in Figure 12. The results are reported in Figure 20 and may be compared with the 14.5mm bore K-Rb results also reported in this Figure.

No systematic measurements of krypton arc diameter were made; however, it was noted that the 10mm lamp operated at 3 kW input power was not wall confined.

6.0 DISCUSSION

1. An optimal match of lamp radiation to the Nd:YAG excitation bands was not obtained with the K-Rb 14.5mm bore lamp, even with a cold spot temperature as low as $40^{\circ}C$. (The vapor pressure of the K-Rb mixture at $40^{\circ}C$ is less than 1 Torr.) Therefore, it appears that an equilibrium vapor pressure situation was not obtained in the lamp. The reason for this may be: 1) the vapor conductance of the tubulation is too small; 2) the arc plasma tends to block the passage of vapor through the opening in the center of the electrode; 3) physical movement of the liquid alkali metal under surface tension forces from the cold spot toward the lamp envelope is occuring, that is, the tubulation is acting as a heat pipe.

   The small bore lamp data obtained on a previous program[1] were reviewed. Rb-K lamps Nos. 22B and 26-1 gave optimal spectral matches at cold spot temperatures below $200^{\circ}C$.[13] This temperature also corresponds to a pressure of less than 1 Torr. Next, a calculation of the vapor pressure in these optimally matched lamps was performed based upon the wavelength spacing of the peaks of the reversed resonance lines. A K-Rb vapor pressure of 10-100 Torr was computed as being presented in the lamps. This figure agrees with the pressures assumed by Schmidt and reported in Figure 5.[7] Schmidt used an indium bath to maintain the cold spot of his lamps at a given temperature. He, too, assumed thermal equilibrium between the cold spot and the alkali metal. His cold spot temperatures were in the $400^{\circ}C$ - $600^{\circ}C$ range and were measured on pure alkali metal filled lamps (no Hg addition).

Liberman, et al.,[3,4] also recorded cold spot temperatures of approximately 500 °C; however, Hg was added to his lamps as a vapor pressure depressant. This indicates that lack of vapor pressure equilibrium also occurred in the lamps studied in the previous program.[1] It did not represent a serious problem for these smaller bore lamps, which require a higher pressure for optimal matching.

Based on the foregoing, a major effort in the next work period must be the development of a technique to establish a controllable alkali metal vapor pressure in the 14.5mm bore alkali metal lamps.

2. The 14.5mm bore K-Rb lamp, even in its over-reversed state, gave a slightly higher effective irradiance measurement (FOV reading) than the 10mm bore krypton arc lamp that this K-Rb lamp is intended to supersede. An optimally matched K-Rb lamp should give an even higher effective irradiance measurement, (at least up to the 1400W lamp input power level to which the present K-Rb lamp has so far been tested).

3. Arc diameter measurements on the K-Rb lamps show that the arcs are not wall confined up to the maximum, 1400W, input power achieved to date. At 1400W input, the arc diameter in the 14.5mm bore lamp is only about 4mm, and the shape of the arc diameter versus input power curve indicates that even at the full rated power of 2.4 kW it will be only about 5mm in diameter. As shown in Figure 19, at 700 W input (the maximum power of the small, 5 and 6.3mm, bore lamps), the arc diameters in the 14.5mm bore lamp and the small bore lamps were about the same, about 4mm. Thus at

higher power (1.4 kW), the arc within the 14.5mm bore lamp operates at more than 3 times the power and current density of the smaller bore lamps, i.e., at 1.13×10^3 W/cm^3 and 108 amp/cm^2, as compared to 400 W/cm^3 and 33 amp/cm^2 for the 6.3mm bore lamp.

Since higher power densities excite higher energy levels in the alkali metal atoms at the expense of resonance radiation transitions, this increase in power density exerts an adverse effect on the effective irradiance of the lamp. Thus, means of expanding the arc should eventually be investigated.[14] Also, the higher excitation level transitions of the alkali metal atoms might be used to pump Nd:YAG; the 0.81μ line of Na is an appropriate higher level nonresonance radiation line that would pump Nd:YAG.

The small arc diameter within the 14.5mm bore lamp, while probably resulting in a decreased lamp effective irradiance, will give a brighter arc. The increased radiance of the arc might well offset the decrease effective irradiance in an imaging cavity, in which this lamp is intended to be used.

4. Increasing the argon vapor pressure from 50 Torr to 3000 Torr did not affect the position of the reversed radiation wings of the optimally matched K-Rb, 6.3mm bore lamps. If the radiation had been due to excited K_2, Rb_2 or K-Rb molecules, a shift of the radiative peaks would have occurred due to a switch of the excited molecular vibrational states. We conclude that the resonance radiation is due to excited atoms. (In contradistinction the

radiation emitted from high pressure, 1000 Torr pulsed lamps is due to a mixture of excited atoms and molecules.)

5. The mercury addition to K-Rb did not increase the effective irradiance of the lamp. The addition of mercury to the K-Rb-(50 Torr argon) mixture does raise the general level of background radiation and also seems to broaden out the long wavelength wing of the reversed resonance radiation. (This latter phenomenon had been noted previously.[3]) This broadening may be due to the appearance of KHg and RbHg molecules, as the pressure of Hg at 500°C is several atmospheres.

6. The use of BeO as an envelope material offers the long range possibility of reducing the bore size of the present 14.5mm bore K-Rb sapphire envelope lamp by increasing the maximum permissible thermal wall loading. A reduced bore size means a physically thinner alkali metal vapor layer through which the resonance radiation must pass, thus enabling an irradiance match to the laser rod to be made at a higher lamp vapor pressure. A thinner walled sapphire envelope would serve a similar purpose as it, too, could also handle high thermal wall loadings.

7. At high power levels, the total radiative efficiency of krypton lamps approaches 50%, and the radiation in the 0.3-1.3μ band is of the order of 39% of the input power. The power density of the lamps can be computed from arc diameter measurements. This information can provide basic information to futher understanding of krypton arc radiative processes.

7.0 CONCLUSIONS

1. An 8 kW (input) alkali metal vapor arc lamp, 10 inches long, with a 14.5mm bore, can be constructed that should pump a Nd:YAG laser more efficiently than an equivalent 8 kW krypton arc lamp. It is not yet known whether the design goal of this contract, 2 kW output in the pumping bands of Nd:YAG, with 8 kW input, can be achieved.

2. A 14.5 mm bore K-Rb lamp produces greater irradiance and total output in the pumping band of Nd:YAG than the equivalent (10mm bore) krypton lamp when both are operated at input powers of 500 W per inch of arc length. The K-Rb lamp was not optimized for pumping Nd:YAG because of lack of control over the vapor pressure of the K-Rb fill. Optimization will probably further increase the superiority of the K-Rb lamp over a krypton arc lamp for pumping Nd:YAG.

3. The power density in the arc of the high power 14.5mm bore K-Rb lamp is a factor of about 3 higher than in the smaller bore lower power K-Rb lamps previously investigated. This may result in somewhat less efficient pumping of Nd:YAG by optimized high power K-Rb lamps than achieved by optimized lower power K-Rb lamps.

4. Additions to the standard K-Rb fill did not improve the lamp's efficiency in pumping Nd:YAG.

5. BeO was successfully tested as an alternative material to sapphire as an alkali metal lamp envelope material. Because of its greater thermal stress capabilities the use of BeO can lead to reduction in lamp bore diameter and thereby improvement in the efficiency in pumping Nd:YAG.

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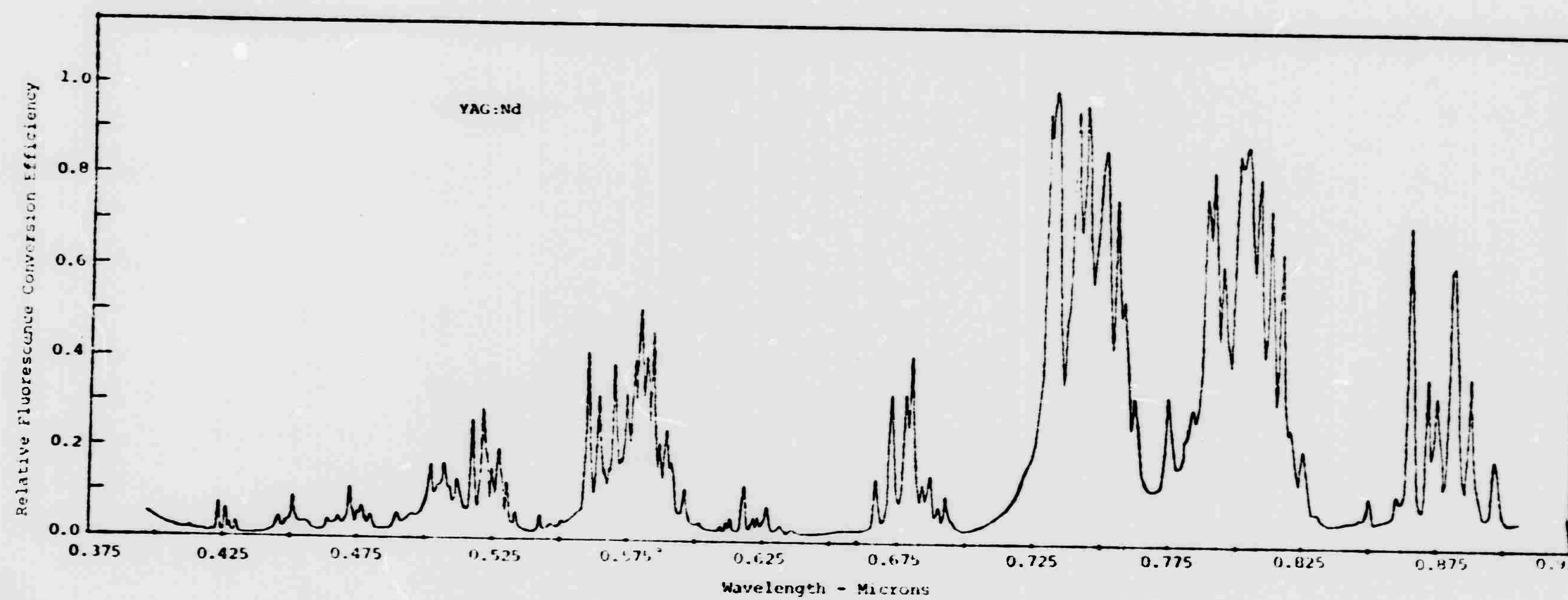


FIGURE 1. EXCITATION SPECTRA FOR Nd:YAG

30

NOT REPRODUCIBLE

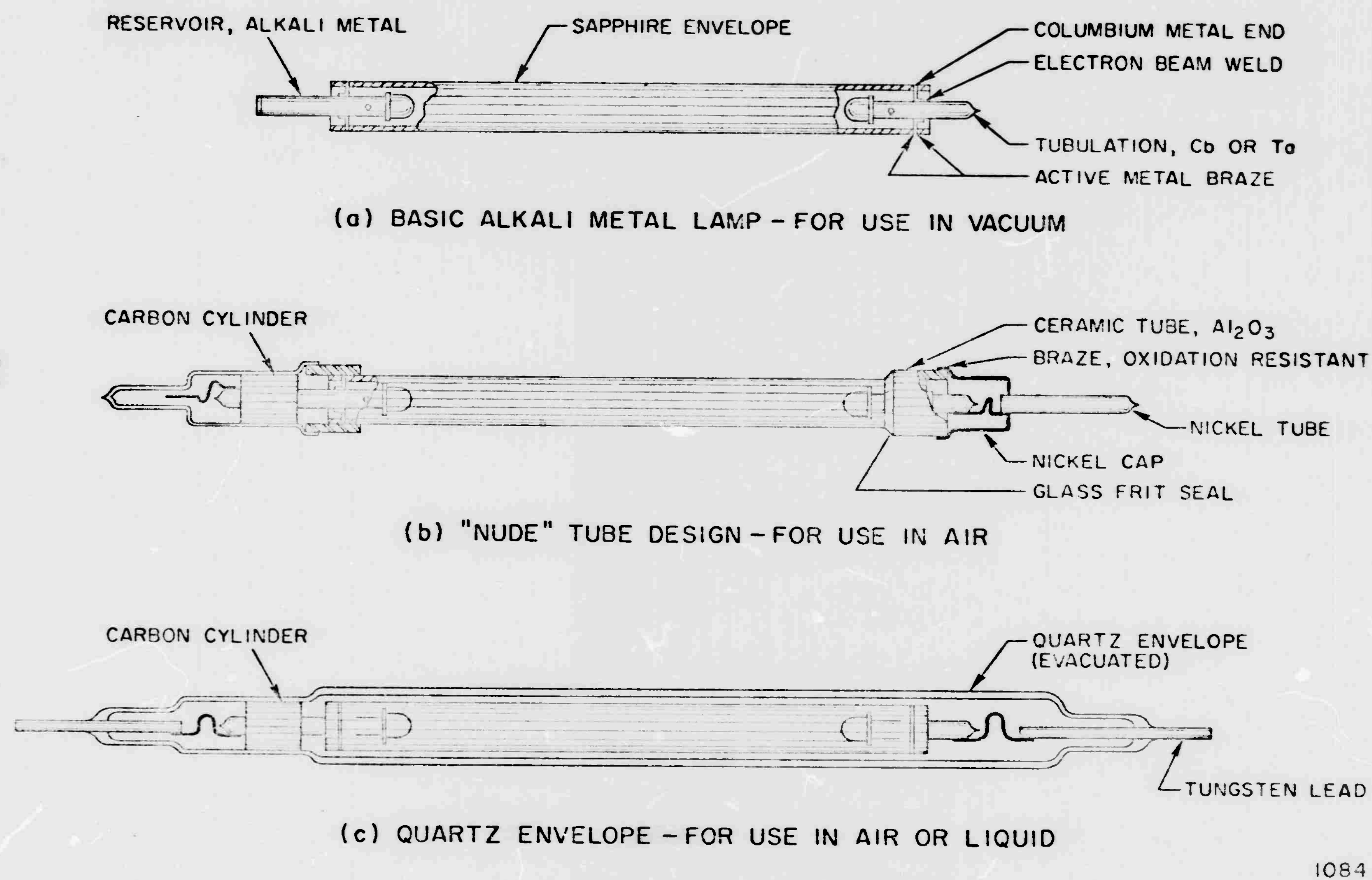


FIGURE 2. SMALL BORE ALKALI VAPOR LAMP DESIGNS

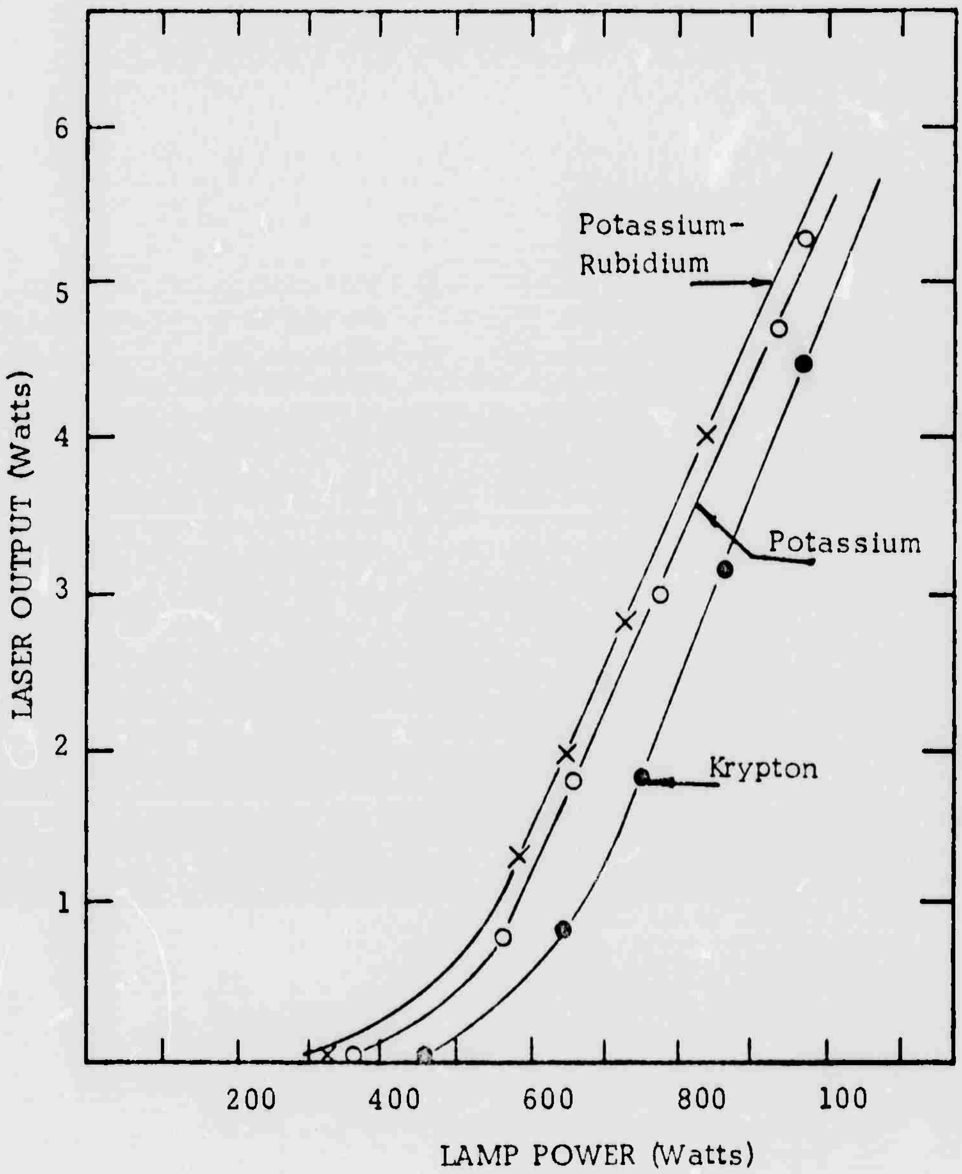


FIGURE 3. LASER OUTPUT AS A FUNCTION OF LAMP INPUT FOR POTASSIUM, RUBIDIUM-POTASSIUM AND KRYPTON LAMPS

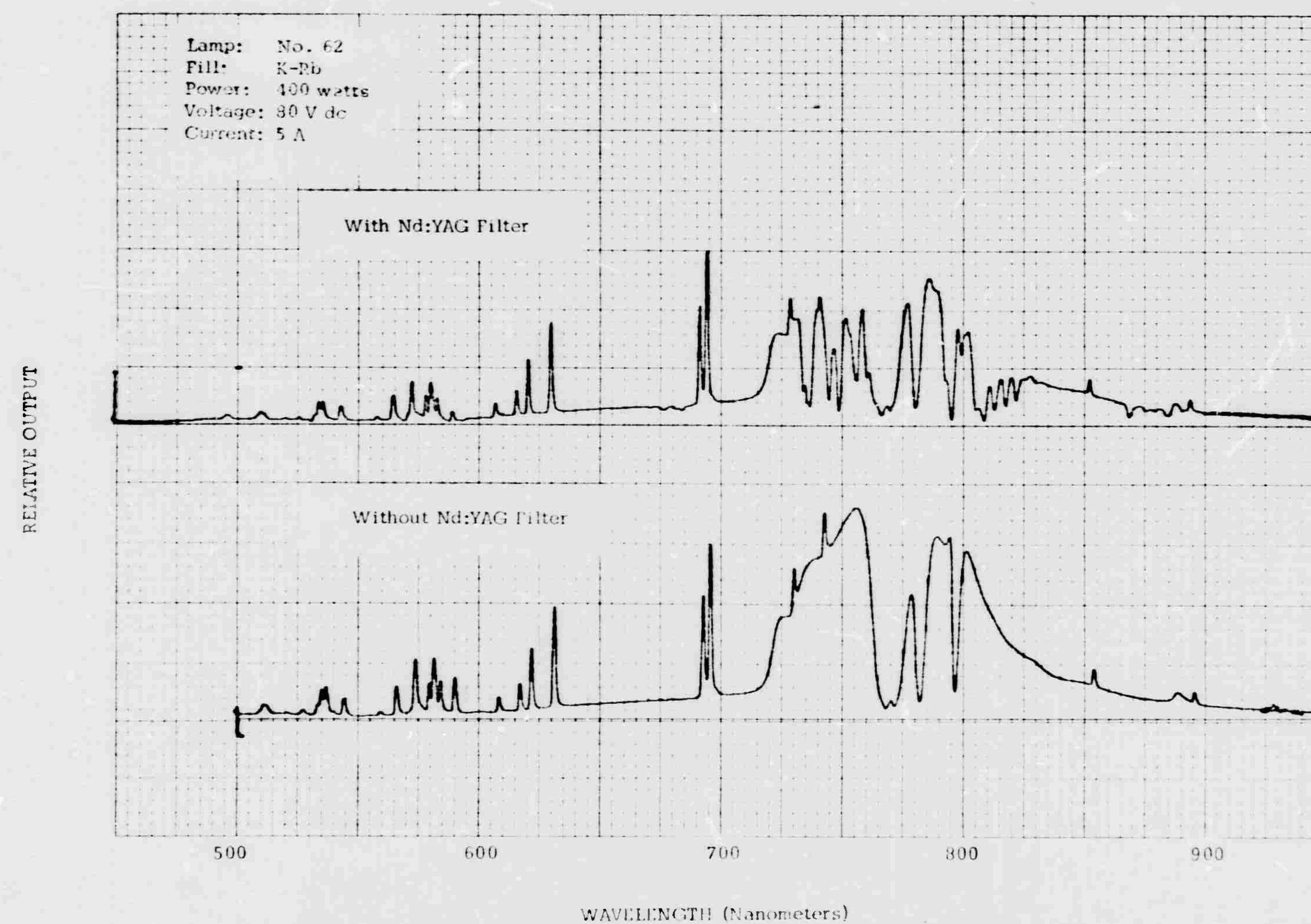


FIGURE 4. EMISSION SPECTRA AND NON ABSORBED RADIATION OF OPTIMUM PRESSURE RUBIDIUM POTASSIUM LAMP

34

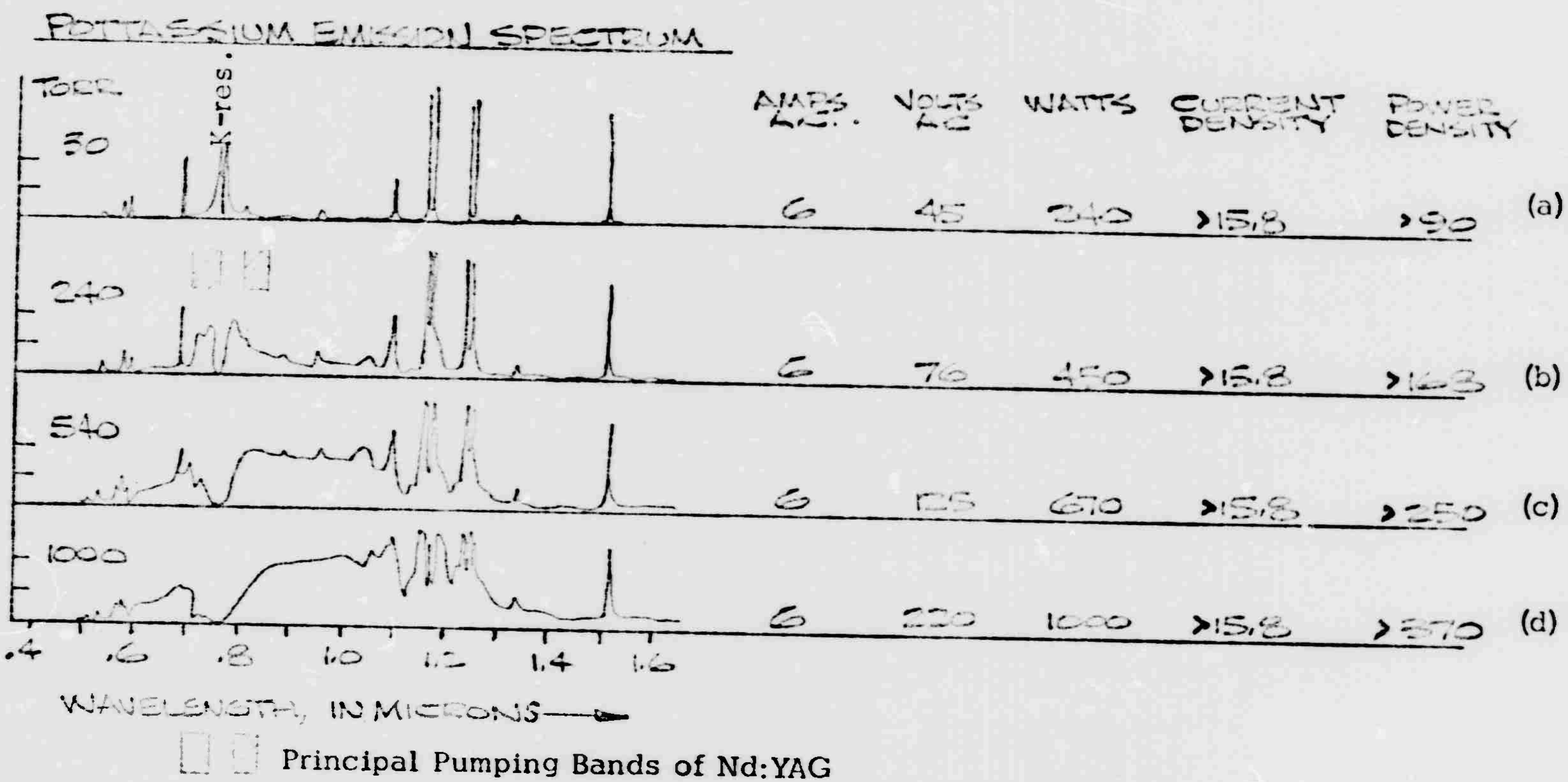


FIGURE 5. POTASSIUM EMISSION SPECTRUM AS A FUNCTION OF PRESSURE

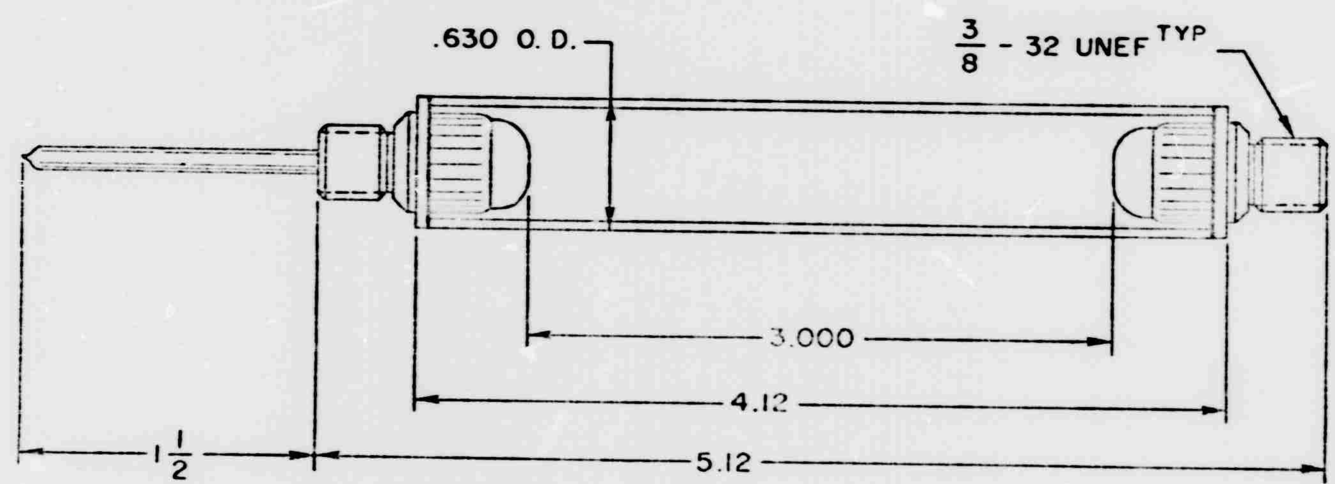


FIGURE 6. ALKALI METAL LAMP 14.5 MM BORE

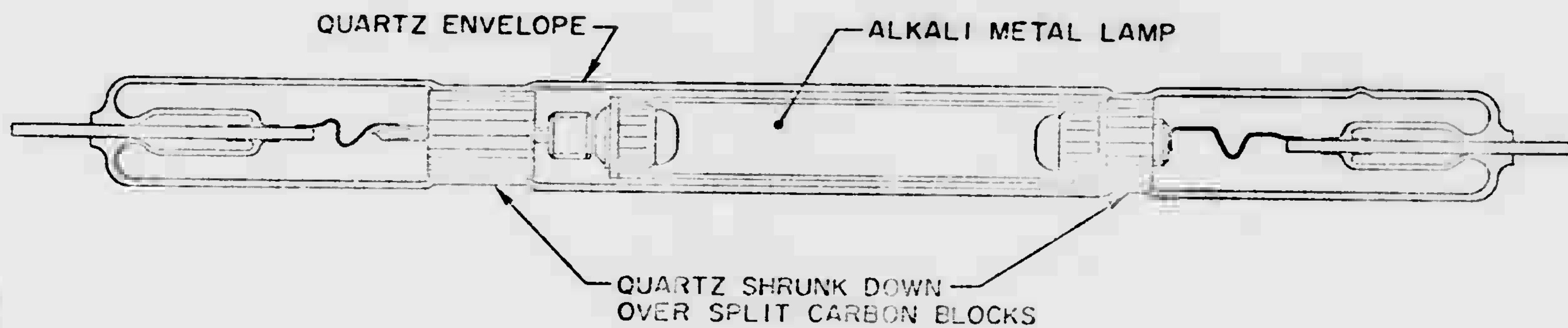


FIGURE 7. ALKALI METAL LAMP IN QUARTZ ENVELOPE

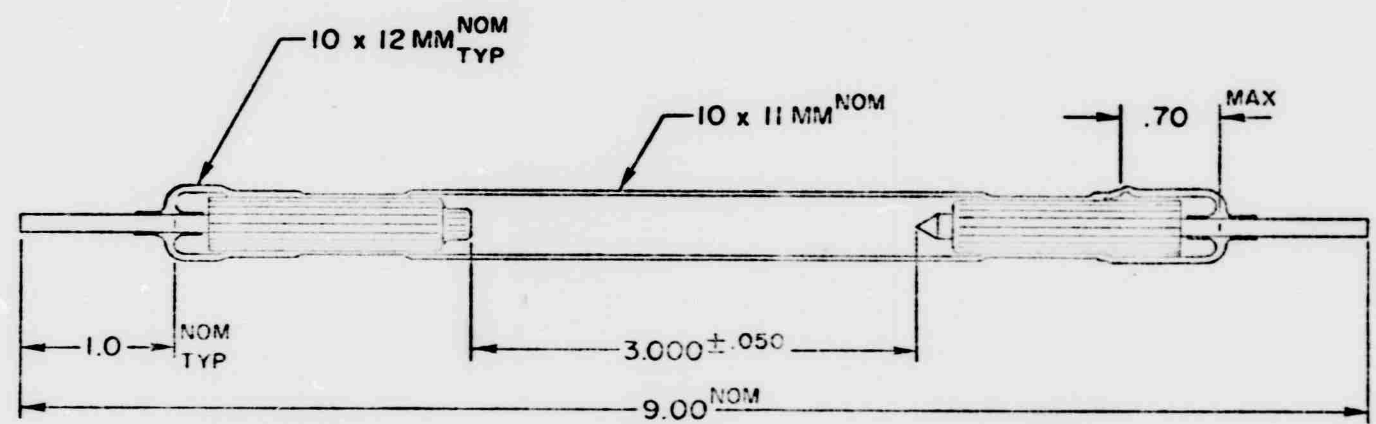


FIGURE 8. KRYPTON ARC LAMP

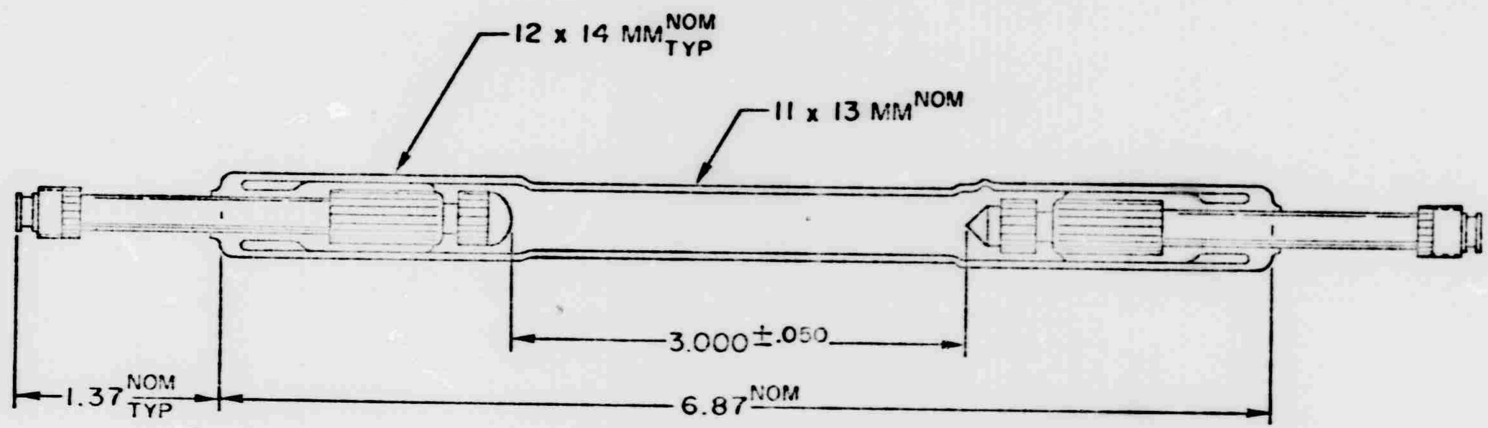


FIGURE 9. KRYPTON ARC LAMP FLUID COOLED ELECTRODES

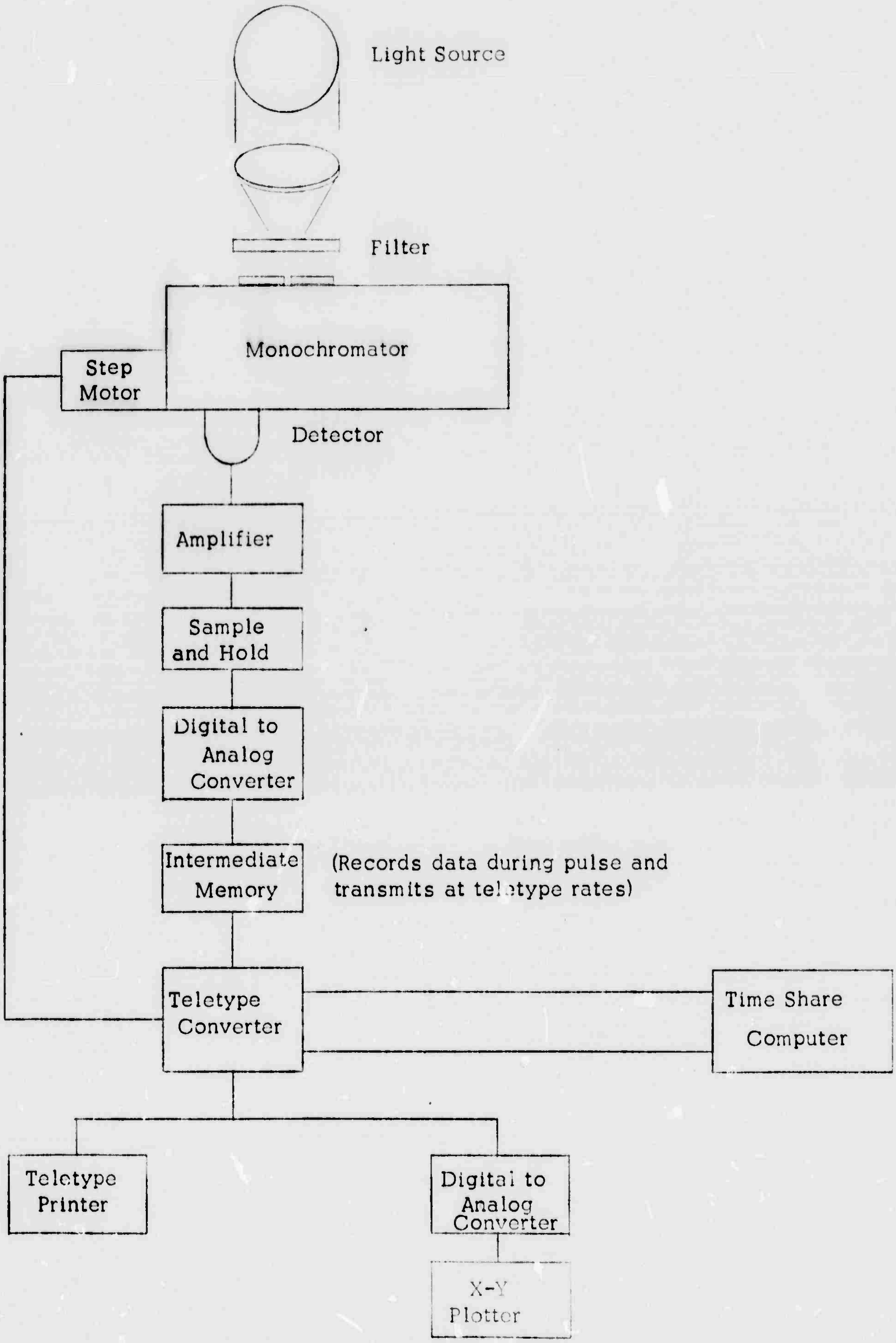


FIGURE 10. SCHEMATIC DIAGRAM OF EQUIPMENT FOR RECORDING LAMP SPECTRA

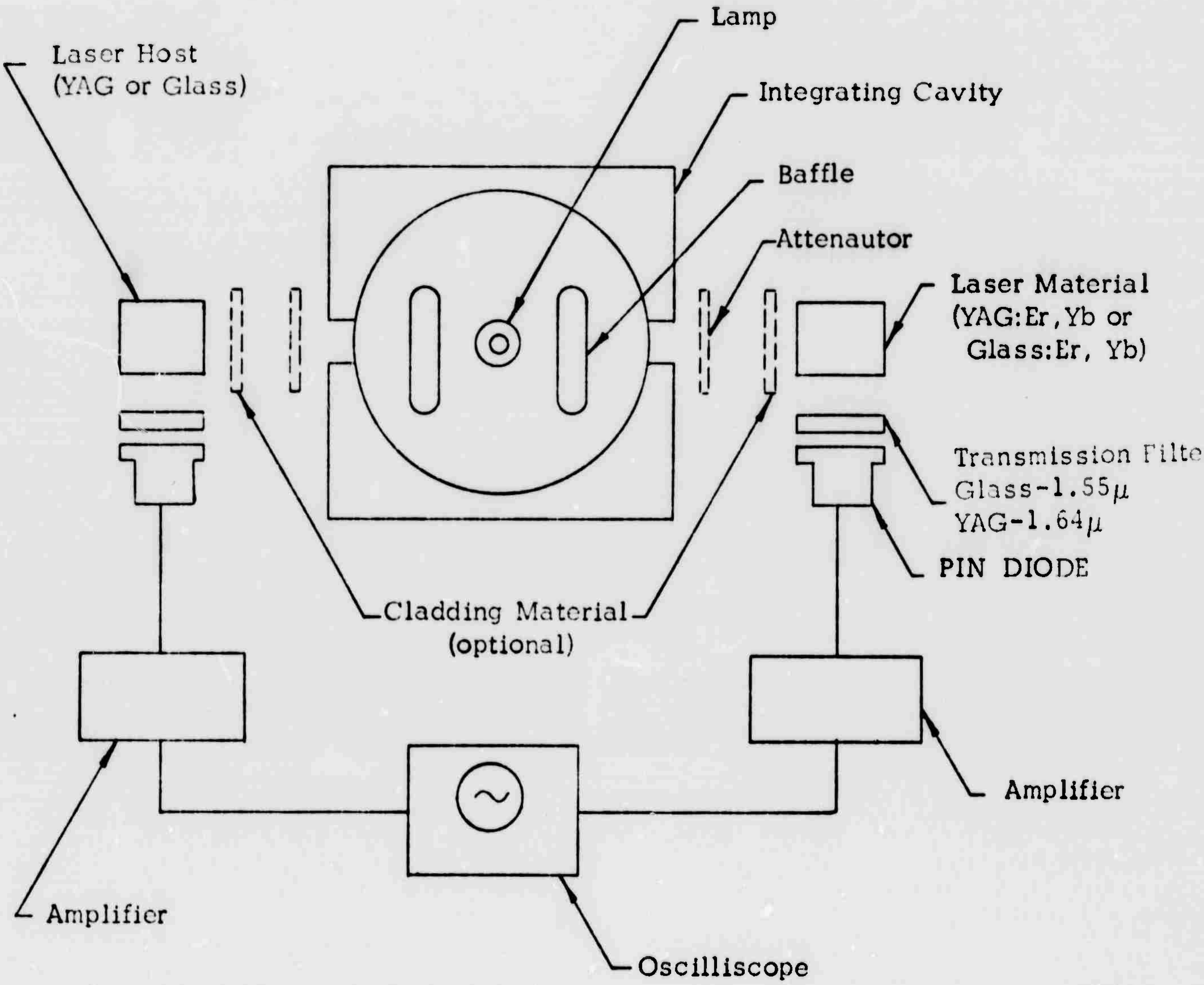
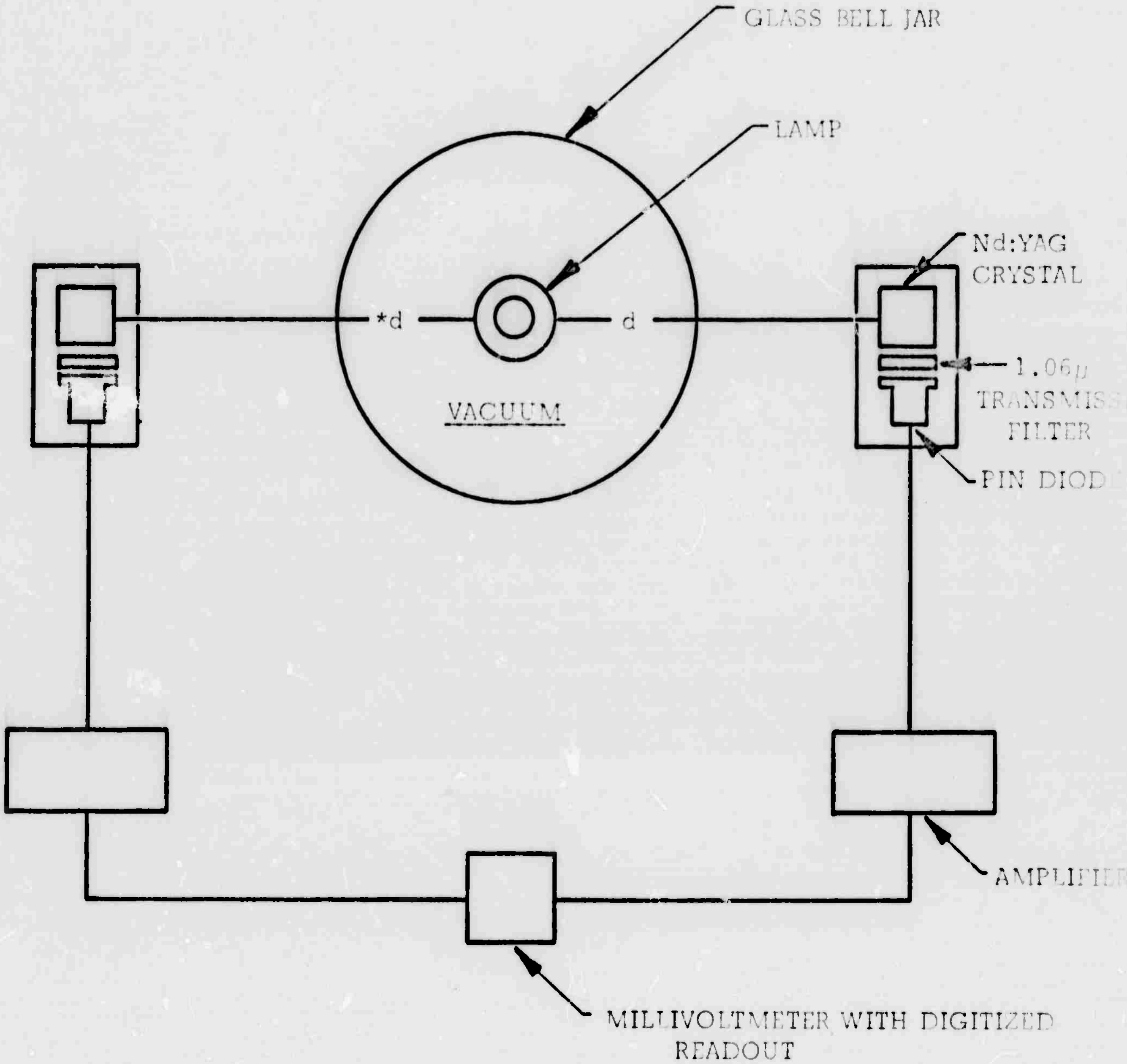


FIGURE 11. FLUORESCENCE ANALYSIS TEST DEVICE WITH LAMP MOUNTED IN INTEGRATING CAVITY



*d is a fixed distance

FIGURE 12. FLUORESCENCE ANALYSIS TEST DEVICE WITH LAMP MOUNTED IN VACUUM BELL JAR

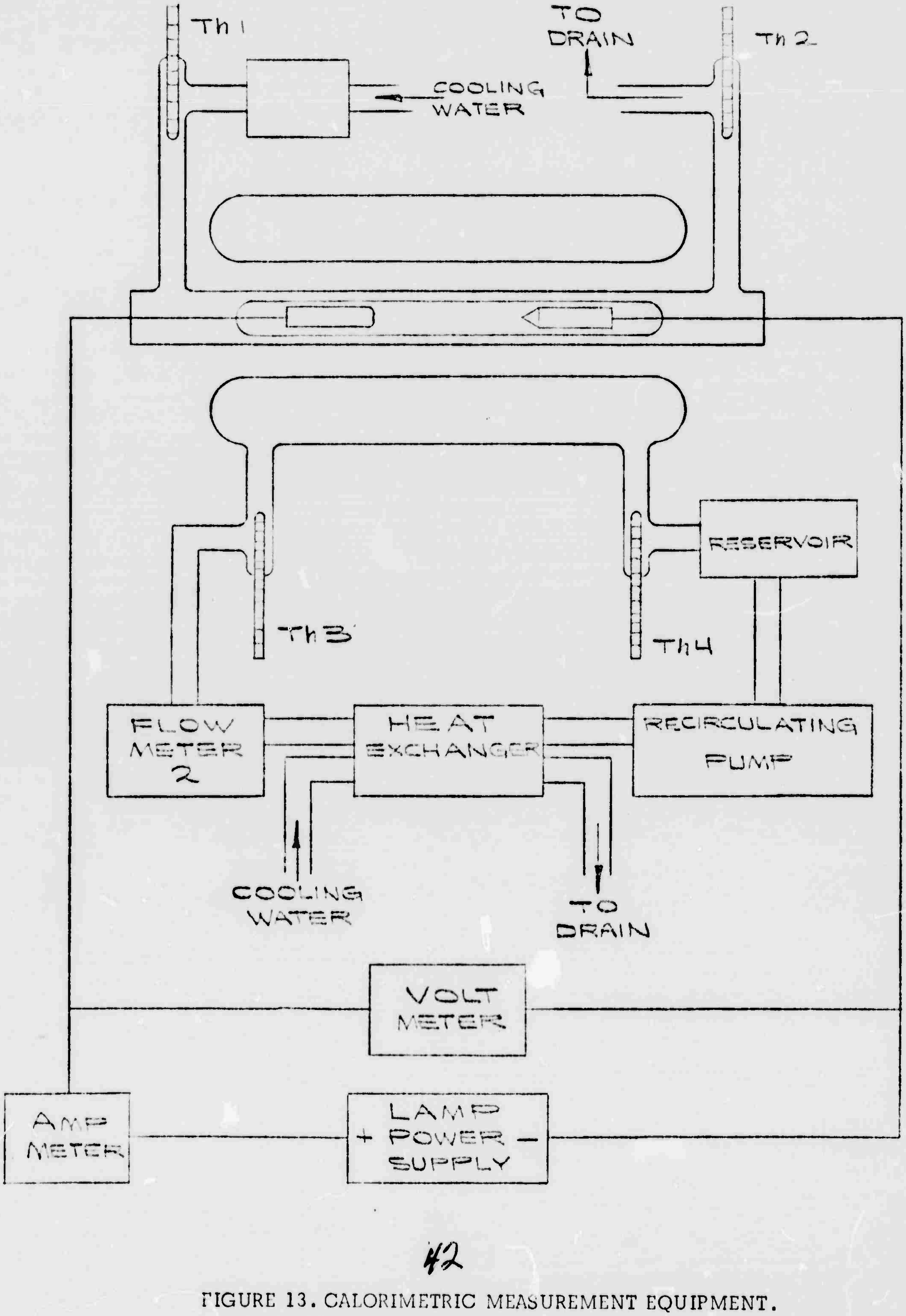
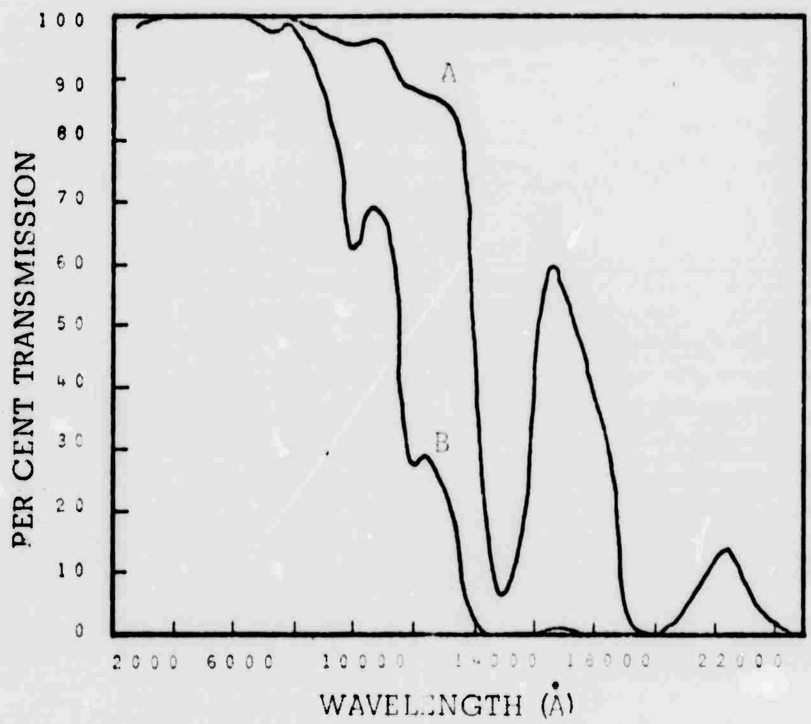


FIGURE 13. CALORIMETRIC MEASUREMENT EQUIPMENT.



Curve A, Transmission for a thickness of 1mm
Curve B, Transmission for a thickness of 1cm

FIGURE 14. SPECTRAL TRANSMISSION OF WATER

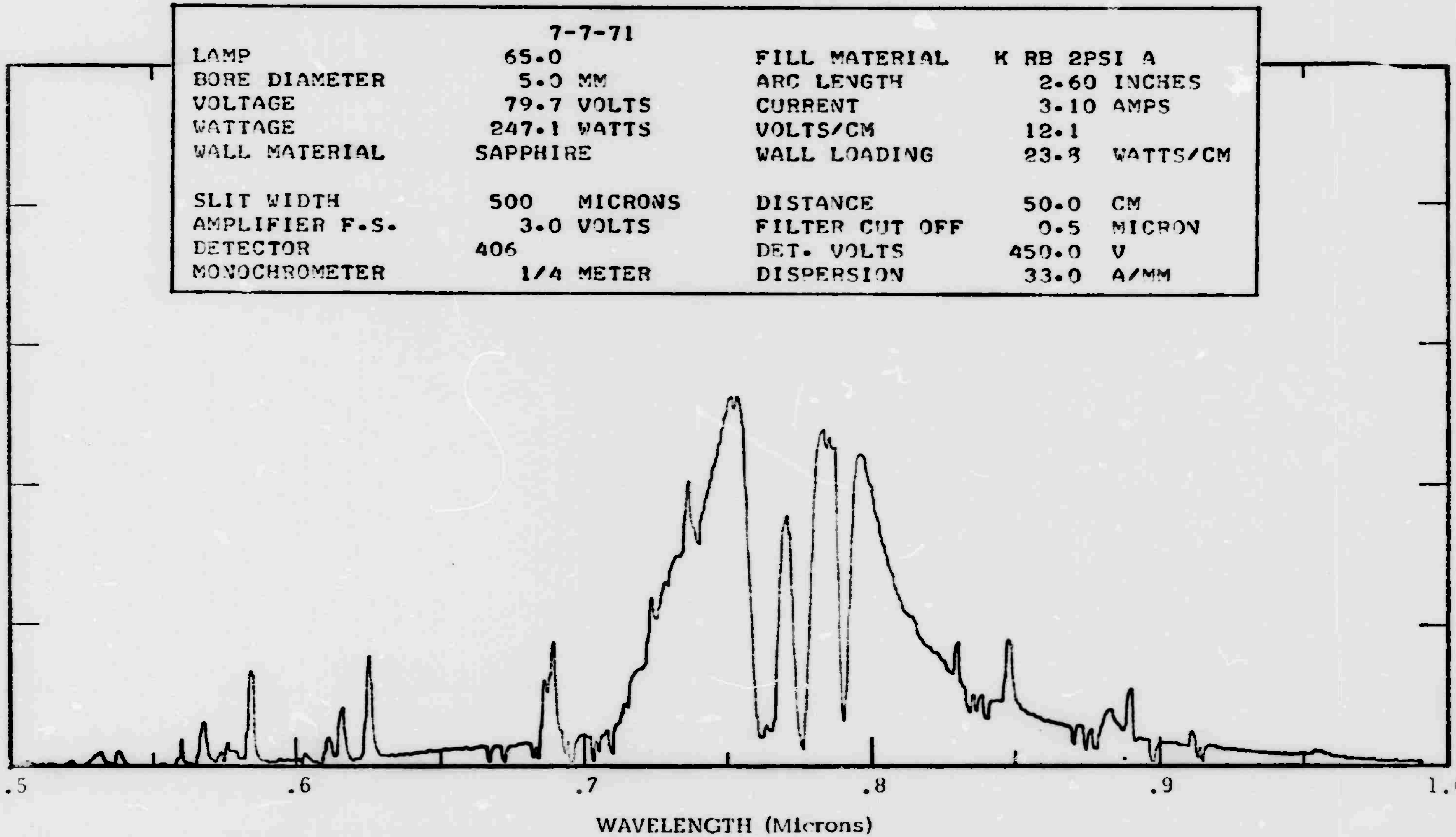


FIGURE 15. SPECTRUM OF K-Rb LAMP WITH 50 TORR OF ARGON, AT OPTIMUM PRESSURE

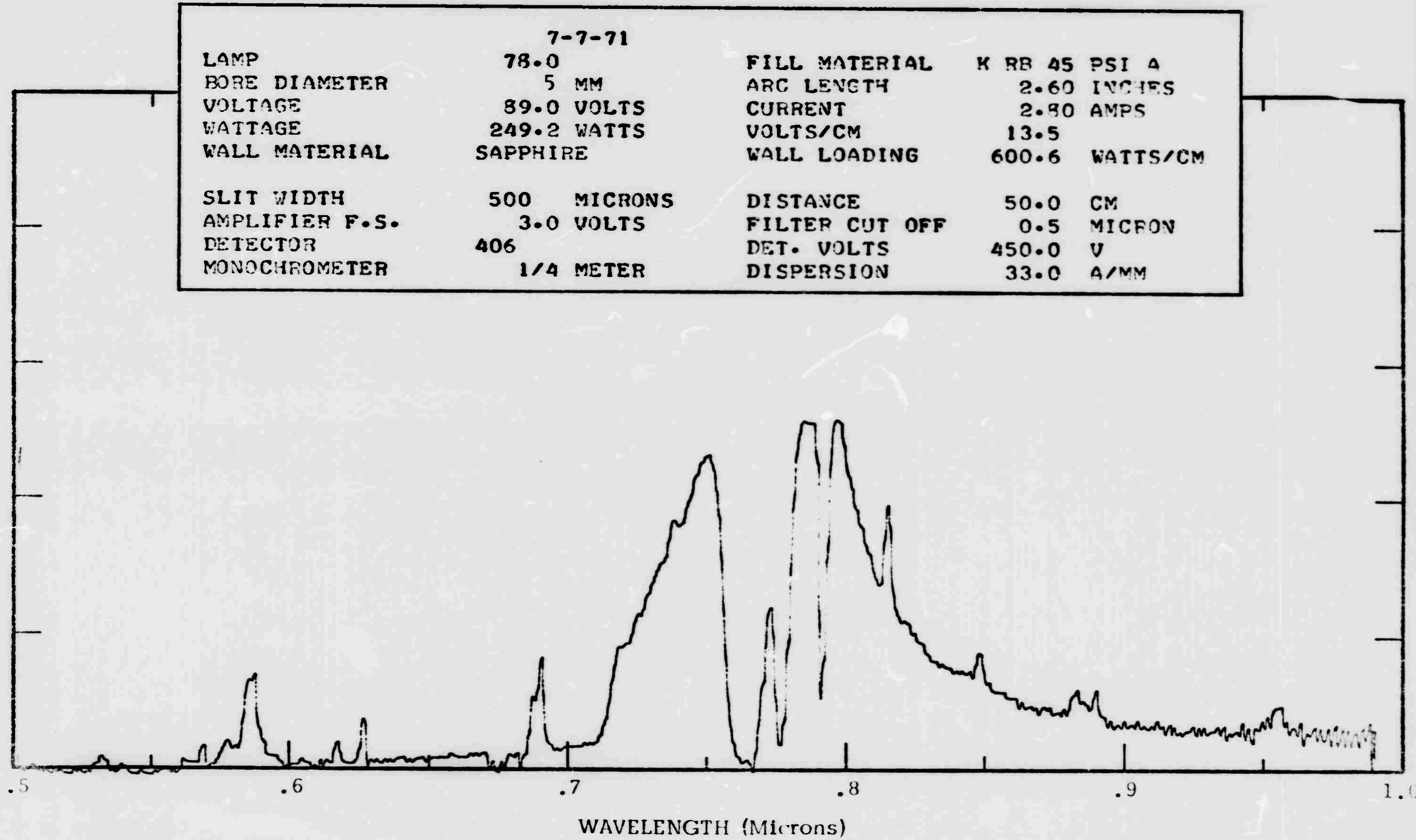


FIGURE 16. SPECTRUM OF K-Rb LAMP WITH 3000 Torr of ARGON, AT OPTIMUM PRESSURE

1/58

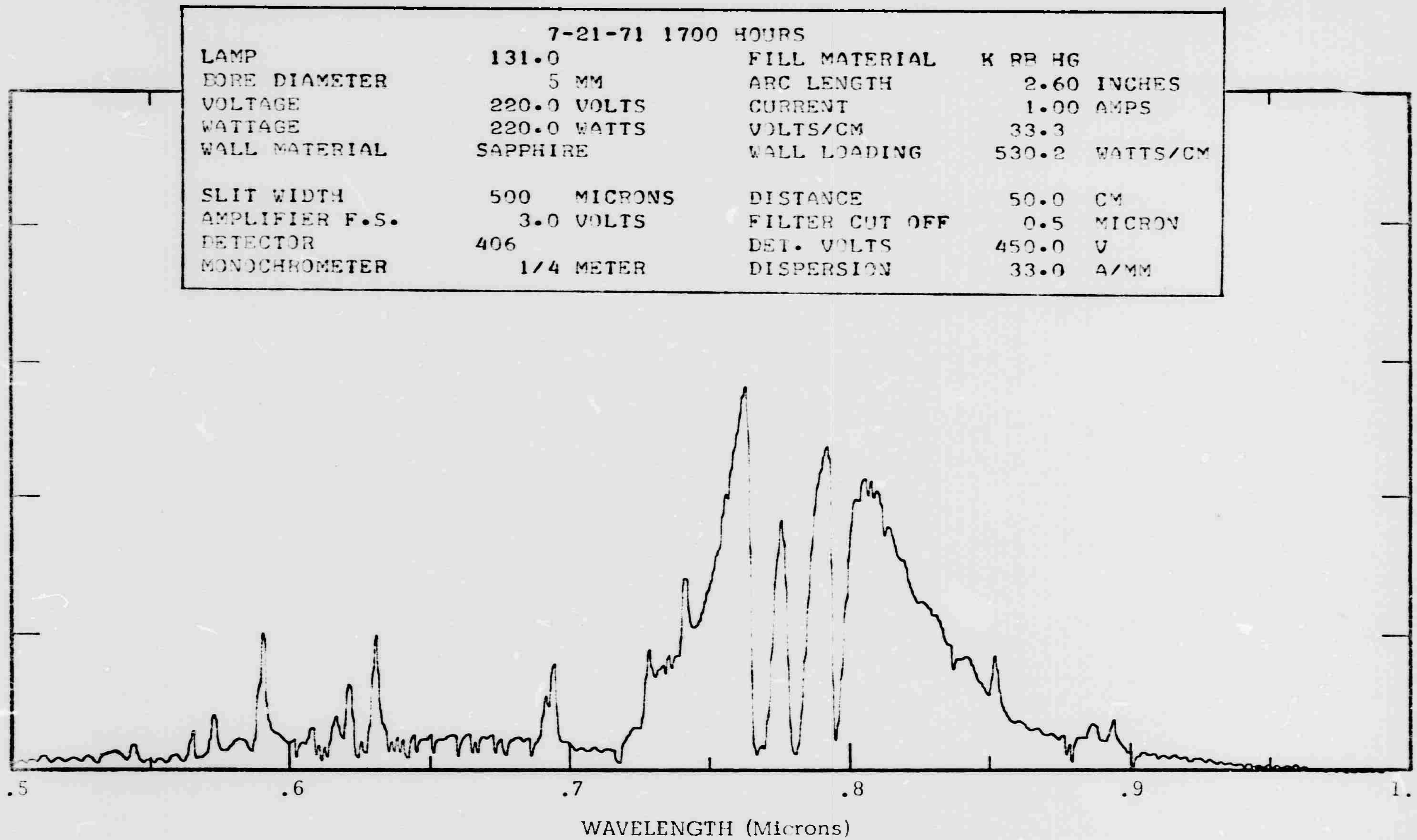


FIGURE 17. SPECTRUM OF K-Rb-Hg LAMP WITH 50 TORR OF ARGON AT OPTIMUM PRESSURE

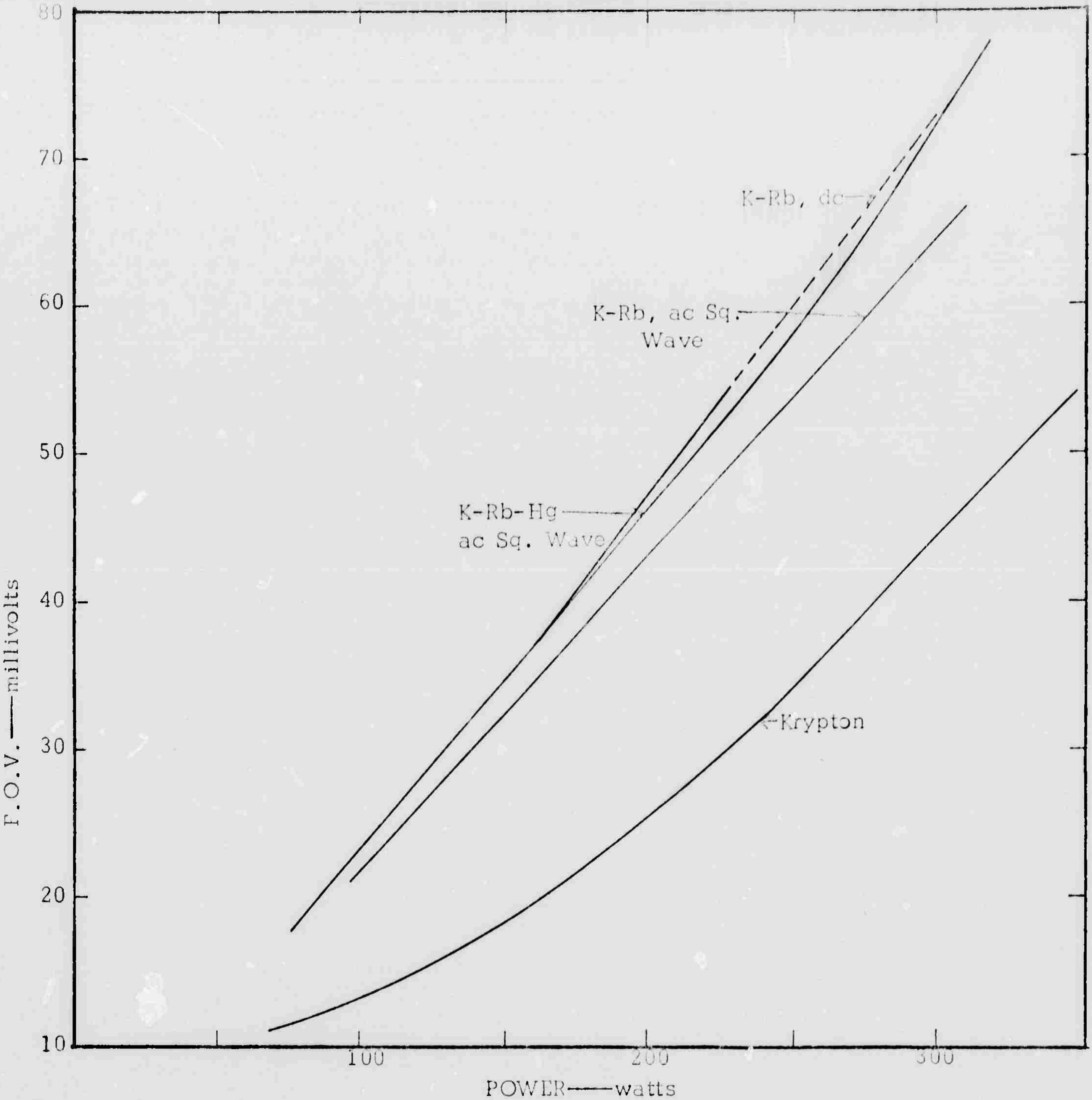


FIGURE 18. FLUORESCENCE POWER MEASUREMENTS FOR ALKALI VAPOR LAMPS AND A KRYPTON ARC LAMP (4 atm, 5mm Bore, 3 Inch Arc Length)

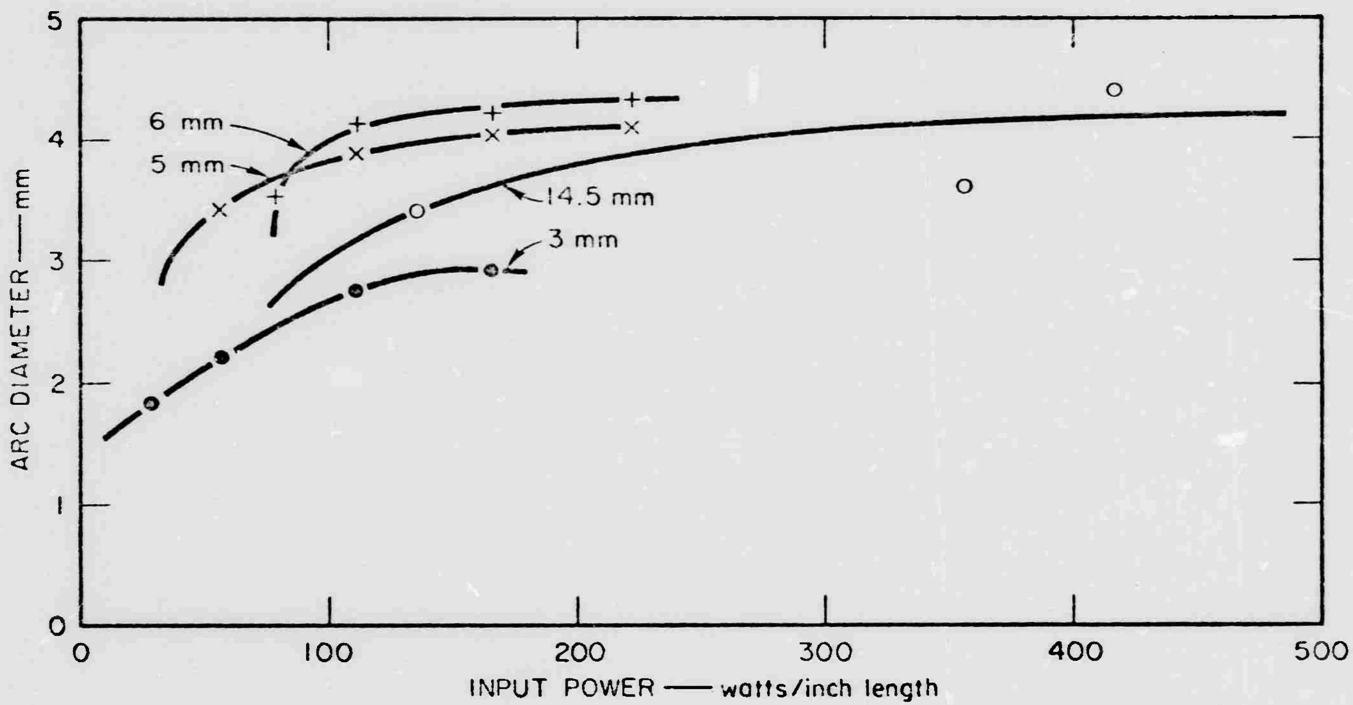


FIGURE 19. ARC DIAMETERS OF K-Rb ARC LAMPS WITH 3, 5, 6.3, and 14.5mm BORE DIAMETERS

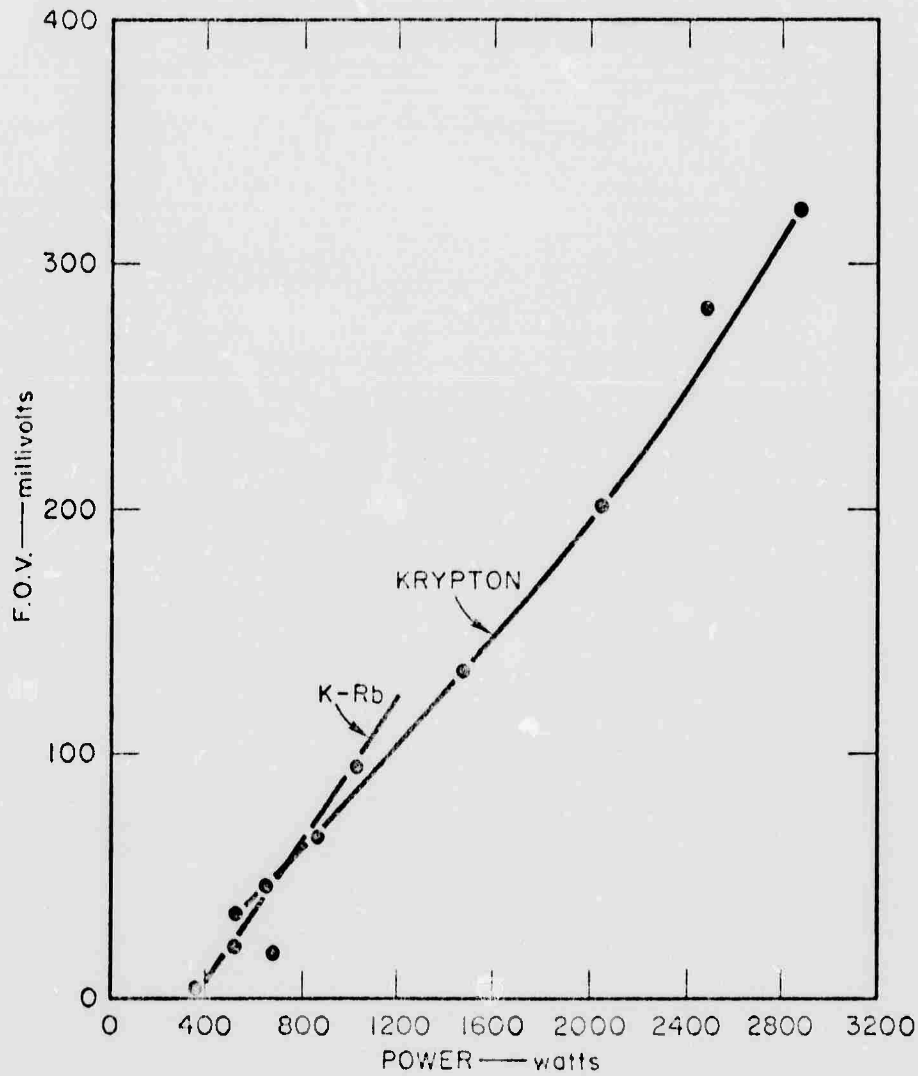


FIGURE 20. FLUORESCENCE POWER DATA FOR 14.5 MM K-Rb AND 10 MM KRYPTON LAMPS.

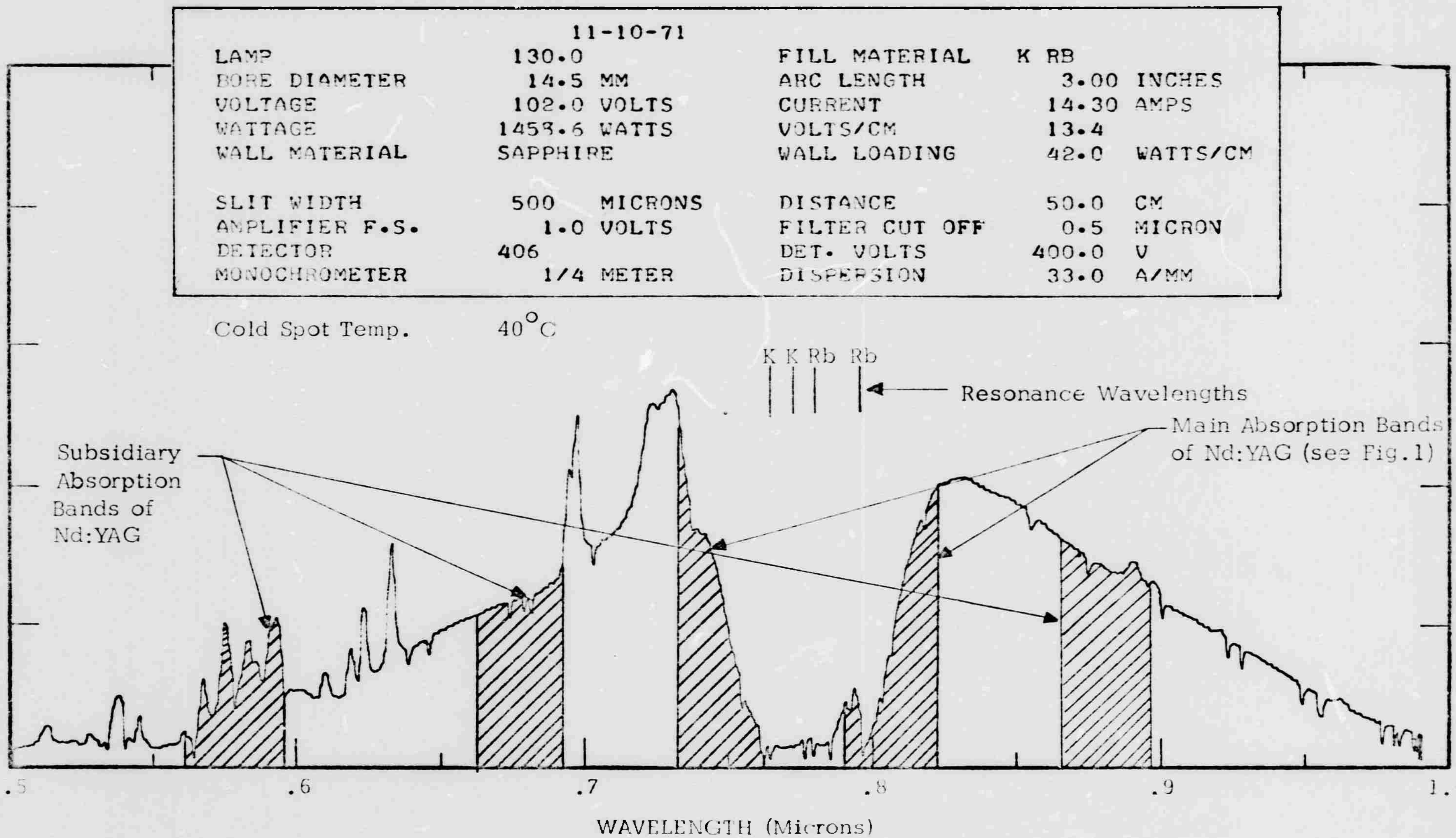


FIGURE 21. SPECTRUM OF K-Rb ARC LAMP WITH 14.5MM BORE DIAMETER ENVELOPE

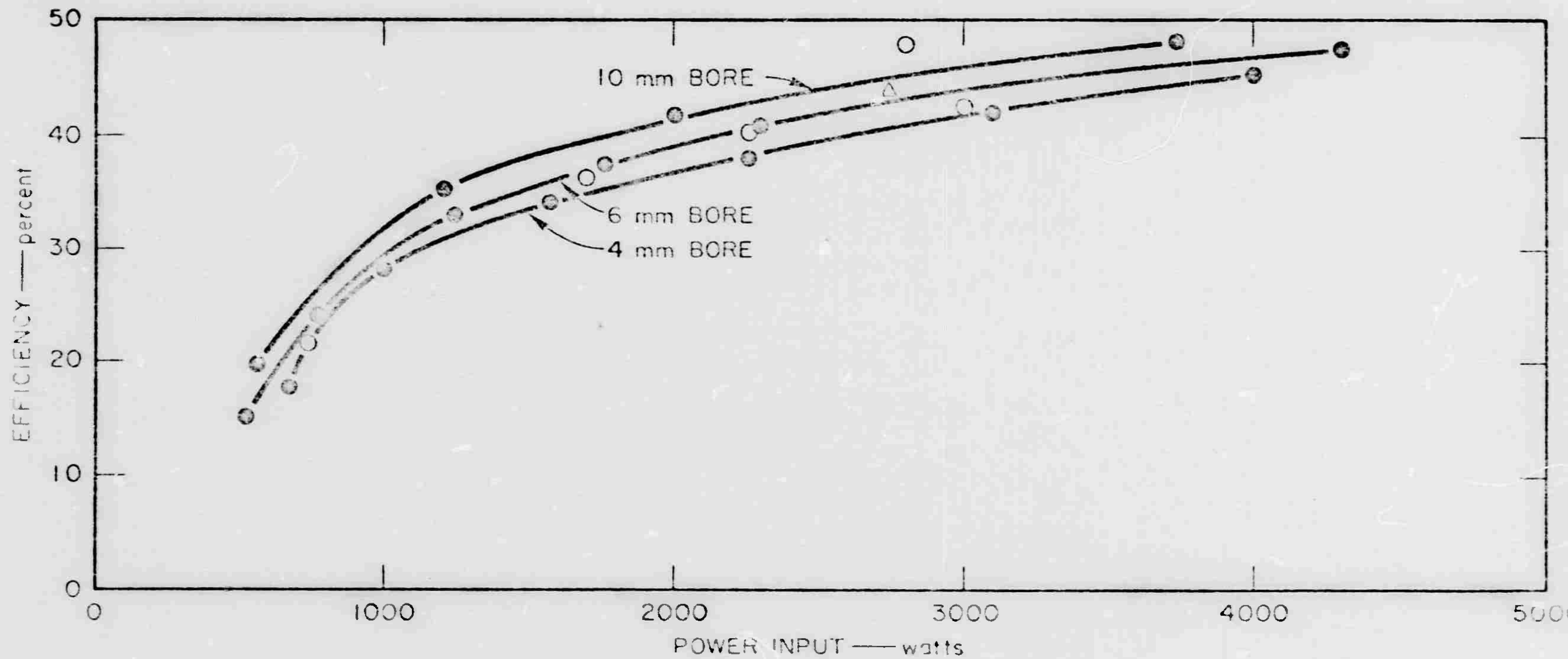


FIGURE 22. KRYPTON ARC LAMP RADIATIVE EFFICEINCY AS A FUNCTION OF INPUT POWER.

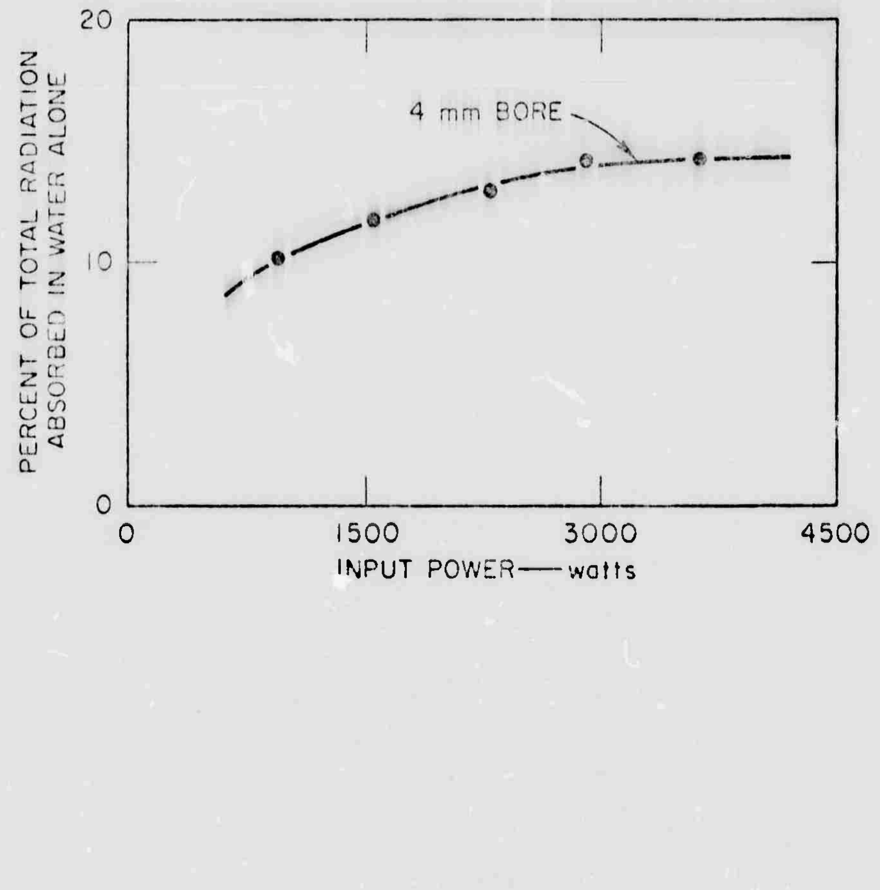


FIGURE 23. PERCENTAGE OF RADIATION FROM 4mm BORE KRYPTON ARC LAMP ABSORBED BY 6mm LAYER OF WATER